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	Engineering and Design CHANNEL STABILITY ASSESSMENT FOR FLOOD CONTROL PROJECTS	
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31 October 1994

US Army Corps
of Engineers

ENGINEERING AND DESIGN

Channel Stability Assessment for Flood Control Projects

ENGINEER MANUAL

CECW-EH-D

DEPARTMENT OF THE ARMY
U.S. Army Corps of Engineers
Washington, DC 20314-1000

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Engineering and Design
CHANNEL STABILITY ASSESSMENT FOR FLOOD CONTROL PROJECTS

1-1. Purpose. This manual provides assistance for determining potential channel instability and sedimentation effects in flood control projects. It is intended to facilitate consideration of the type and severity of stability and sedimentation problems, the need for and scope of further hydraulic studies to address those problems, and design features to promote channel stability. The concept of channel stability implies that the plan, cross-section, and longitudinal profile of the channel are economically maintainable within tolerable limits over the design life of the project. Causes and forms of instability are discussed in paragraph 3-3.

1-2. Applicability. This manual applies to all HQUSACE elements, major subordinate commands, districts, laboratories, and field operating activities having civil works responsibilities.

1-3. References. Required and related publications are listed in Appendix A.

FOR THE COMMANDER:

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Chief of Staff

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DEPARTMENT OF THE ARMY
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Chapter 1
Introduction

1-1. Purpose

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1-2. Applicability

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1-3. References

Required and related publications are listed in Appendix A.

1-4. Explanation of Terms

Abbreviations used in this manual are explained in the Notation (Appendix D).

1-5. General Approach

The approaches presented in this manual are mainly qualitative and are intended to assist the engineer in the early stages of project formulation to forecast the type and magnitude of channel stability problems. Confidence in the stability of the project design will be enhanced if several different techniques of stability and sedimentation evaluation are employed. Wherever possible, the procedures employed should have been developed under hydraulic and geomorphic conditions similar to those encountered in the project. If procedures appropriate to project conditions do not seem to be available, or if different methods of evaluation do not give similar results, a need for more sophisticated analyses may be indicated. Such analyses might involve quantitative sediment transport studies and numerical modelling of morphologic response, which are not covered in this document. Engineer Manual (EM) 1110-2-4000 suggests three stages of sediment studies: sediment impact assessment, detailed sedimentation study, and feature design sedimentation study. This manual should be useful in the first stage of the staged sedimentation study, and design guidance documents listed in Appendix A should be used in the second and third stages. The reader should refer to EM 1110-2-4000 for the risks and consequences of using the "staged study" approach.

1-6. Discussion

Adverse effects of flood control modifications on channel stability and sedimentation may be more common than is generally known. Linder (1976) wrote:

> "Once disturbed, a stream channel begins an automatic and relentless process that culminates in its reaching a new state of equilibrium with nature....In the past, too many problems...have been handled by modifying the river channels involved without giving thought to the sediment being transported by the water.... Techniques should be employed that consider sediment transport characteristics and stream equilibrium....The ultimate cost of the uncontrolled erosion and excessive downstream sediment deposition that follow traditional channel modification is often far greater than the initial cost of a design that recognizes the influence of sediment transport characteristics on a stream's state of equilibrium."

Channel instability and sedimentation in a flood control project are not always the result of project modifications to the hydrology or channel characteristics. They may also reflect the continuation of pre-existing conditions such as meandering. Potential consequences of channel instability, whether pre-existing or project-induced, include reduction of assumed flood conveyance, loss of land and structures, and excessive requirements for maintenance or rehabilitation.

1-7. Systematic Approach to Channel Stability

Solution of channel stability problems in the planning and design of a flood control project requires the synthesis of field information, analytical procedures, and previous experience in a complex fashion that cannot easily be summarized as a linear sequence of steps. The flowchart shown in Figure 1-1 is intended to convey how data assessment and analysis can be integrated to attack stability problems. Numbers within the diagram blocks indicate subsequent paragraphs in this manual.

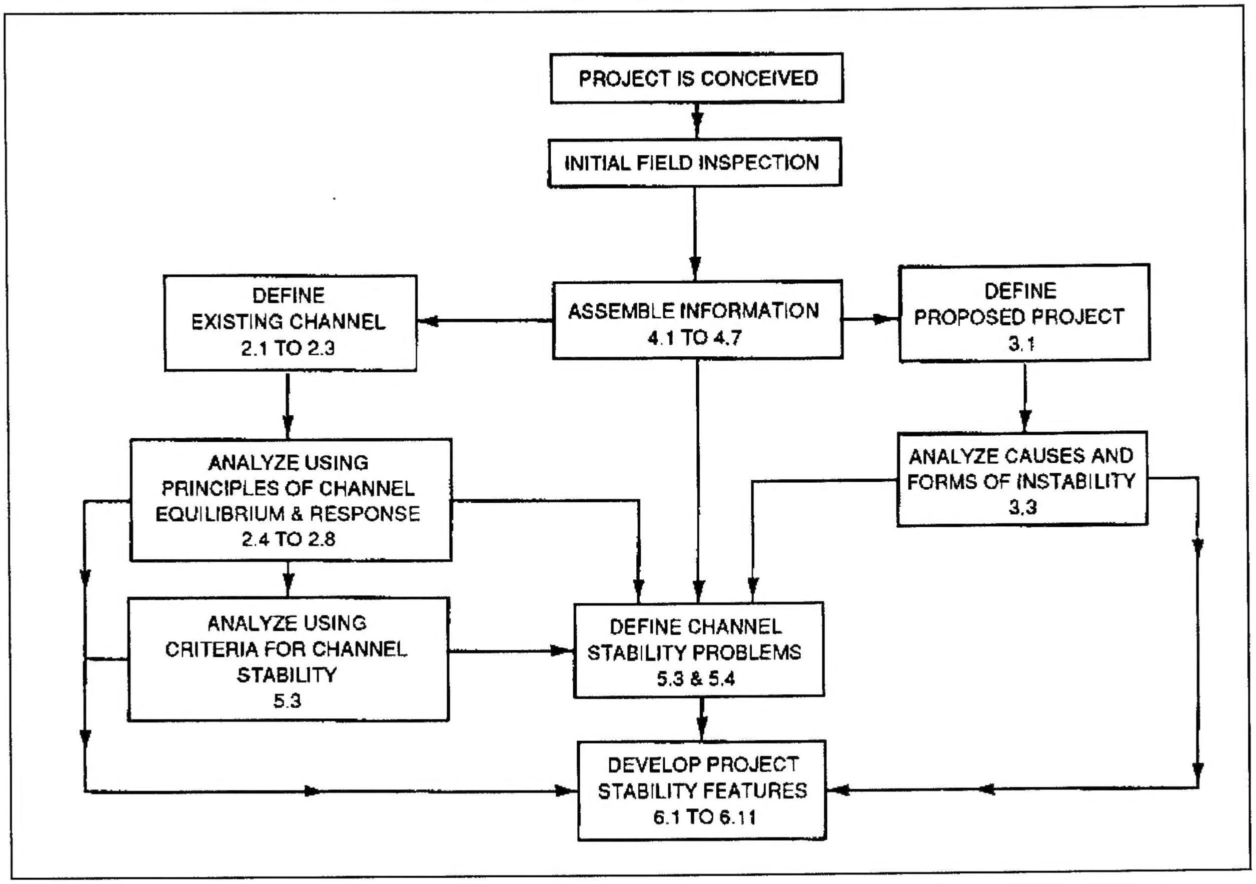


Figure 1-1. Flowchart for systematic approach to channel stability

Chapter 2
Channel Stability Principles

Section 1
Characteristics of Channels in Erodible Materials

2-1. Geomorphic Context

a. In undertaking a stability and sedimentation assessment of a proposed flood control channel project, it is important to understand the relationship of the project length to the stream system and the basin geomorphology, and to see the project channel as part of an interlinked system. *Geomorphology* here means the relationship of stream channels and floodplains to the geology and physiography of the region. Factors that have produced the present channel features and will affect the response of the channel to engineering works include sources and supply of sediments, basin materials and vegetation, catastrophic events, earth movements, landslides, eruptions and major floods, changes in land use and development, and past interferences including structures, dredging, and diking. The existing condition of the channel may depend on factors far removed in space and time, and instability response to flood control works may affect locations beyond the project length far into the future.

b. In general terms, a drainage basin can be divided into three main zones: an upper erosional zone of sediment production, a middle zone of sediment transport with simultaneous erosion and deposition, and a lower zone of sediment deposition (Figure 2-1). The actual situation is often more complex, because local geological controls or other factors can produce local depositional zones in the upper basin or local erosional zones in the lower basin. Flood control projects are more common in the middle and lower zones where the stream overflows frequently onto agricultural or urban land. Methods of estimating sediment production or yield are described in Chapter 3 of EM 1110-2-4000.

c. In the general case, the longitudinal profile of the stream system tends to flatten through time by degradation in the upper reaches and aggradation in the lower reaches (Figure 2-2). In most natural systems this process is slow enough to be of little engineering concern; but where the stream system has been interfered with in the historical period, profile flattening may be proceeding at noticeable rates. In some channelization projects, response of this type has been dramatic (see Chapter 3 for examples).

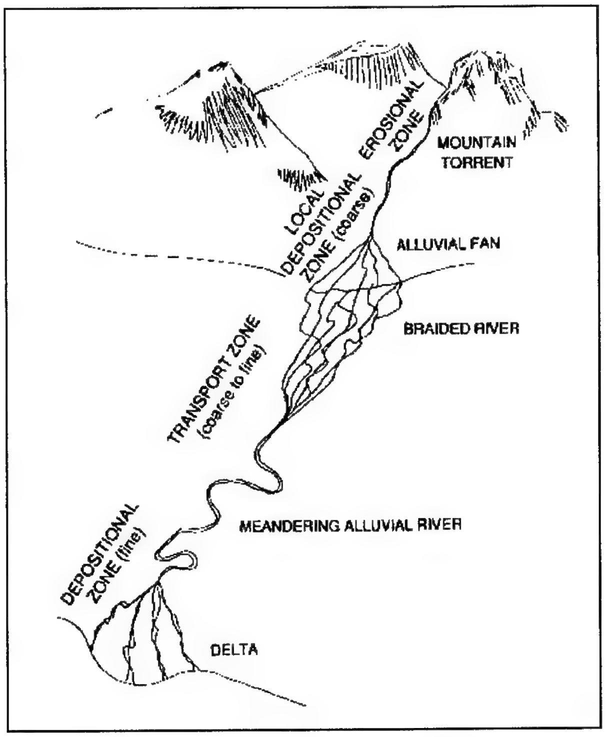


Figure 2-1. Drainage basin zones and some channel types

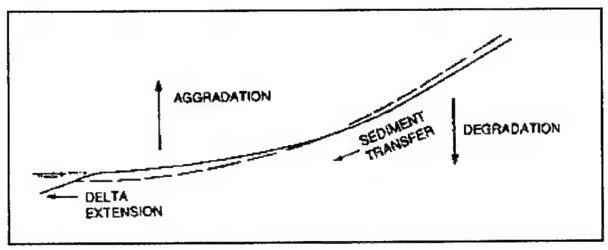


Figure 2-2. Typical longitudinal stream profile and direction of change through time

d. Methods of investigating basin and channel system geomorphology include examination of maps, surveys, hydrologic records, and aerial photography and satellite images; aerial and ground reconnaissance; study of geological and soils reports; analytical methods; and consultation with local residents and specialists. The amount of study necessary or feasible depends on the scale of the project and the judged severity of potential instability problems. In the past, hydraulic design studies for flood control channels often gave insufficient attention to stability and sedimentation aspects. Where stability was addressed, insufficient attention was given to long-term effects and responses beyond the project area.

e. Selected references on the geomorphology and hydraulics of stream systems are listed in Appendix A.

2-2. Common Channel Types

A number of common channel types and their characteristic stability problems are described below and summarized in Table 2-1.

a. Mountain torrents. These are high-velocity streams on steep slopes, often exhibiting a sequence of drops and chutes controlled by large boulders, fallen timber, etc. (Figure 2-3). Erosion and deposition are sometimes confined to severe flood events. Some mountain torrents on very steep slopes are subject to the phenomenon of "debris flows" or "debris torrents" whereby under severe flood conditions the bed becomes fluid and a virtual avalanche of boulders and gravel runs down the mountainside.

b. Alluvial fans.

(1) Alluvial fans generally occur where a stream emerges from a mountain valley onto relatively flat land (Figure 2-4). They are depositional features usually characterized by coarse alluvial materials and unstable multiple channels subject to frequent shifts or "avulsions." The main channel is often "perched" on the highest ground. Sometimes the alluvial fan is inactive depositionally, and the stream is eroding into earlier deposits. They are usually easily recognizable on aerial photographs and sometimes on topographic maps. In wooded country they are not always easily recognized on the ground.

Table 2-1
Some Stream Channel Types and Their Characteristic Stability Problems

Channel Type	Typical Features	Stability Problems
Mountain torrents	Steep slopes Boulders Drops and chutes	Bed scour and degradation Potential for debris flows
Alluvial fans	Multiple channels Coarse deposits	Sudden channel shifts Deposition Degradation
Braided rivers	Interlacing channels Coarse sediments(usually) High bed load	Frequent shifts of main channel Scour and deposition
Arroyos	Infrequent flows Wide flat channels Flash floods High sediment loads	Potential for rapid changes in planform, profile, and cross section.
Meandering rivers	Alternating bends Flat slopes Wide floodplains	Bank erosion Meander migration Scour and deposition
Modified streams	Previously channelized Altered base levels	Meander development Degradation and aggradation Bank erosion
Regulated rivers	Upstream reservoirs Irrigation diversions	Reduced activity Degradation below dams Lowered base level for tributaries Aggradation at tributary mouths
Deltas	Multiple channels Fine deposits	Channel shifts Deposition and extension
Underfit streams	Sinuous planform Low slope	Meander migration
Cohesive channels	Irregular or unusual planform	Variable

Figure 2-3. Mountain torrent

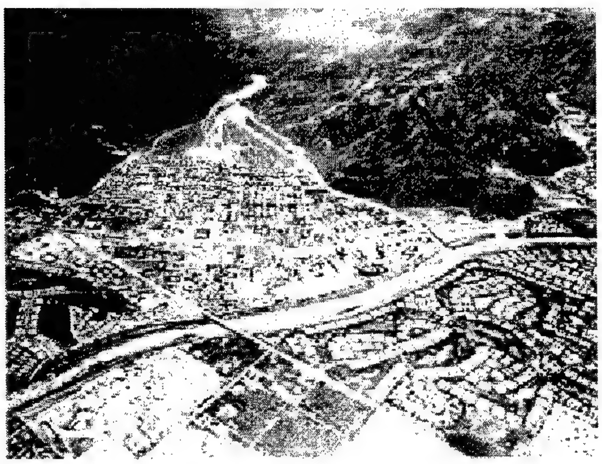


Figure 2-4. Alluvial fan

(2) Potential stability problems on alluvial fans include avulsion of the stream at a point upstream of training works or channelization, thereby bypassing the works, and infilling of the designed conveyance channel by coarse sediment deposits. Flood control works should be carried sufficiently far upstream and consideration should be given to trapping or removal of coarse sediment upstream of the flood control zone. Location of the flood control channel requires consideration of local features and processes.

c. Braided rivers. Braided rivers consist of a network of interlacing channels with unstable bars and islands (Figure 2-5). They generally occur in the upper and upper-middle zones of a basin. Bed materials are usually gravels or cobbles, but braided sand rivers are found occasionally. Bed material transport tends to be high, at least in flood periods. Stability problems include how to maintain the channel through transport of the bed material load and how to avoid serious disturbances of the longitudinal profile. Points that require consideration are the planned cross section, the alignment in plan, and provision for future shifting and erosional attack.

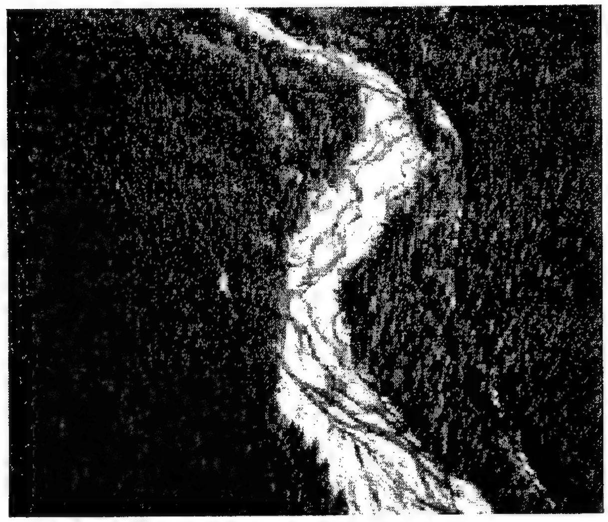


Figure 2-5. Braided river

d. Arroyos. Arroyos are streams in deserts and arid areas that are dry much of the time but carry large discharges and heavy sediment loads under occasional flood conditions (Figure 2-6). The channel may be deeply incised into the terrain in some reaches and liable to frequent overspill in others. Because of the heavy sediment loads, infilling by deposition can occur very quickly if velocities are reduced by enlargement, weirs, or other works.

Figure 2-6. Arroyo

e. Meandering alluvial rivers.

(1) These generally occur in the middle and lower zones of a basin. The single channel follows a characteristic sinuous planform and is normally eroding into the floodplain on one bank and creating new floodplain by deposition on the opposite bank. Bed material is usually sand or sand and gravel. In undisturbed natural systems, future shifting of the channel is often predictable from comparison of sequential maps or aerial photographs. In many cases the traces of former channel locations are detectable on aerial photographs (Figure 2-7).

(2) Numerous stability and sedimentation problems may arise from flood control works on meandering streams. Flood control may involve straightening, regulation or augmentation of flows, and alteration of sediment loads. Meandering systems are often sensitive to modest imposed changes and can respond with troublesome alterations of cross sections, planforms, and gradients. Planning requires consideration of past channel behavior, of likely responses, and of the advisability of stabilization measures.

f. Modified streams.

(1) In some regions, many streams have been modified in the past by human activity and do not much resemble natural rivers. A common form of modification is straightening or enlargement for flood control; but if the changes occurred many decades ago, the details may be difficult to discover. Another form of modification is by flood control works or reservoirs on a parent river, which produced changes in the stream of interest by altering base levels.

(2) A particular regional type of modified stream is exemplified by the incised channels of northern Mississippi (Figure 2-8). These are hill streams in erodible soils that often have a long history of response to widespread basin erosion following land-use changes, channelization, and/or altered base levels. Planning of flood control works on a stream of this type should take into account its present state of evolution toward a new equilibrium.

g. Regulated rivers. These are generally streams where the flood discharges have been reduced and the low flows increased by upstream storage reservoirs (Figure 2-9). Such streams often exhibit a reduction in morphologic activity compared with previous natural conditions, and the cross sections of their channels may have been reduced by deposition of sediment and encroachment of vegetation. But if the stream under natural conditions carried substantial loads of bed material, trapping of sediment in reservoirs may initiate slope changes downstream. The effects of regulation on stability are thus complex and depend on the previous characteristics of the stream as well as on the degree and mode of regulation.

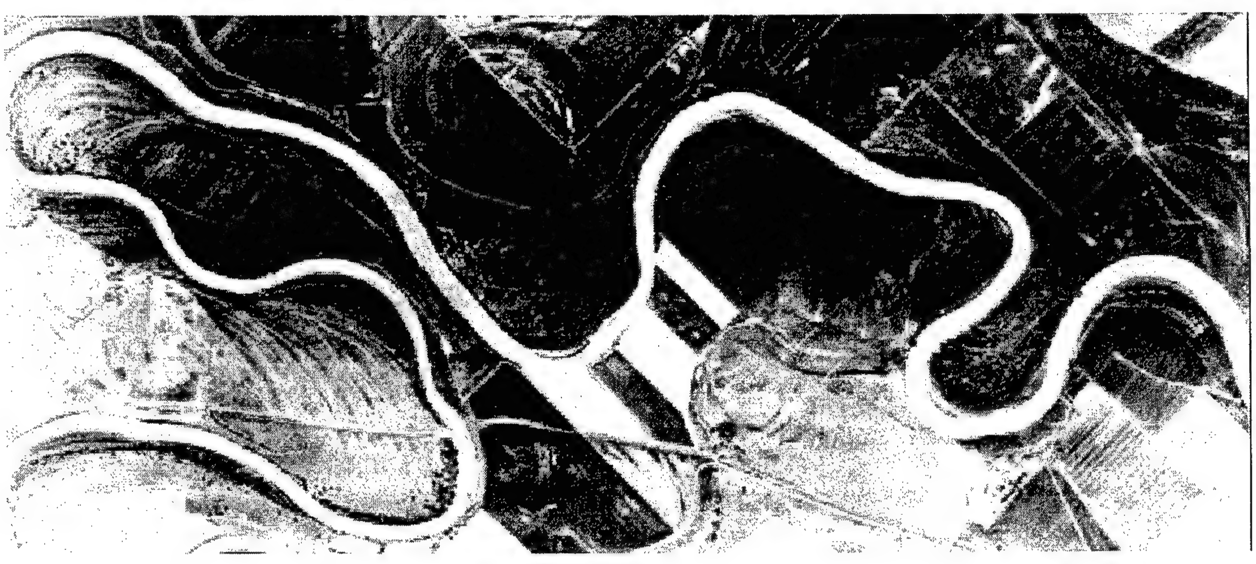


Figure 2-7. Meandering alluvial river

Figure 2-8. Incised channel

Figure 2-9. Regulated river

h. Deltas. Deltas somewhat resemble alluvial fans but occur on flat slopes where a river discharges into still water and deposits its sediment load (Figure 2-10). Under natural conditions the river splits into a number of distributaries, whose bed levels rise over time as the delta extends into the water body. Flood control levees adjacent to deltas can require periodic raising, particularly if the river is confined artificially to a single channel. The potential for channel avulsions upstream of the works requires consideration.

i. Underfit streams.

(1) Underfit streams are common in glaciated regions such as the northern Great Plains. They are generally small, irregularly sinuous streams occupying a wide valley bottom that was formed and occupied by a much larger stream - usually the outflow from a glacial lake - near the end of the last glacial period. The slope along the valley bottom tends to be quite flat, and the underfit stream is usually of low velocity, relatively stable, with well-vegetated banks. Sometimes the planform is highly contorted.

Figure 2-10. Delta

(2) Underfit streams are also found throughout the country in abandoned river courses and as a result of flood control works such as levees and reservoirs. Underfit streams can sometimes be realigned and shortened without creating instability problems. However, there are also many instances in which shortening might cause severe instability problems.

j. Cohesive channels. Channels in cohesive materials may be found in a variety of environments including glacial till plains, coastal marine deposits, filled lakes, etc. Channels in till tend to have irregular planforms: the occurrence of an occasional sequence of regular meanders may indicate intersection with an infilled alluvial channel. In uniform marine clays, channels sometimes exhibit a series of uniform wide flat meanders easily distinguished from meanders in alluvial materials. The stability of channels in cohesive materials may vary widely, but it is generally greater than in alluvial materials.

2-3. Channel Geometry and Processes

Channel geometry has four main components: planform, cross section, slope (gradient), and bed topography. The term "channel processes" generally refers to natural changes in planform, cross-sectional boundaries, longitudinal profiles, and bed topography.

a. Planforms.

(1) Stream planforms were once roughly classified as braided, meandering, and straight; but a wide variety of natural forms are now recognized. Figure 2-11 shows a more extended set of descriptions with associated environmental conditions.

(2) Relationships between planform and other aspects of geometry and processes are difficult to systematize, although often appreciated intuitively from long experience of river observation. For example, braided rivers are usually wide and shallow, and the limits of the braided area tend to remain relatively stable. Certain types of sinuous planform generally indicate a systematic process of down-valley meander migration, while others indicate a process of periodic bend cutoffs. Streams with highly contorted meandering planforms tend to have relatively flat slopes and low width-to-depth ratios. Figure 2-12 attempts to summarize available information on channel pattern, type, and associated variables, and Figure 2-13 illustrates various forms of meander shifting. The total length of most natural streams does not change appreciably over time despite dynamic changes in planform and channel location. For example, local shortening produced by occasional meander bend cutoffs is usually compensated for by gradual lengthening of other bends. Where overall shortening is imposed, the stream often responds by attacking banks and developing new meanders in an attempt to restore the original length.

b. Cross sections.

(1) The cross section of a natural channel depends on basin runoff, sediment input, and boundary soils and vegetation, as explained further in Section II. Under natural conditions the average cross section usually does not change much over a period of years, but it may alter temporarily in severe floods. Systematic trends of enlargement or shrinkage usually result from changes in discharge or sediment inputs as a result of basin changes or on-stream works. The variability of cross sections from point to point along the channel depends on many factors: it may be quite small in stable nearly-straight channels, and very large in highly active channels of complex planform.

(2) The process of cross-section enlargement by erosion is easy to visualize. The mechanism of shrinkage is less easy to visualize and varies considerably (Figure 2-14). In a more or less straight channel, it can occur as a result of deposition of suspended sediment on the banks and subsequent colonization by vegetation. In a shifting meandering channel, shrinkage will occur if the rate of deposition on the inner bank of bends exceeds rate of erosion on the outer bank.

(3) A method for comparing cross sections along a channel reach, or for establishing an average cross section to estimate overall channel characteristics, is to establish a sloping reference plane parallel with the average water surface of a substantial but within-bank flow. The elevation of the reference plane is then transferred to each cross section for visual comparison of sections relative to the plane. Widths and areas can be determined at various levels above and below the reference plane, and can be averaged to indicate average section properties at various levels relative to the plane. The same reference plane should be used as a basis for successive surveys to compare changes over time.

(4) When hydraulic computations of channel capacities and water surface profiles are made for active mobile-boundary streams, it is important to realize the transitory nature of cross sections. Although the average channel cross section over a long reach may be similar under low-water and flood conditions, individual cross sections may change substantially according to the stage of flow. For example, bends and scour holes in meandering channels normally deepen in floods, and points of inflection ("crossings") tend to shoal. When water surface profiles are modelled using standard computational procedures based on fixed boundaries, boundary mobility must be considered and a sensitivity analysis performed if necessary.

(5) Further hydraulic difficulties with unstable cross sections arise when in-channel flows are to be systematically increased as a result of flood control, for example, by construction of floodplain levees close to the channel. If the channel is left in its natural state, it may enlarge systematically over a period of time as a result of erosion by the increased flows. Actual flood levels would then tend to be lower than those computed using existing cross sections. On the other hand, if the channel is designed to be enlarged by excavation, the cross sections provided may be partly infilled by sediment deposition, in which case actual flood levels would be higher than computed. A common error in designing modified channels for flood control is to provide too large a cross section, intended to carry a rare flood without overbank flow. Such a cross section is unlikely to maintain itself because it partly infills with sediment under more frequent flood conditions. Although a need for dredging or excavation to maintain the enlarged channel may be recognized and provided for in project agreements, experience has shown

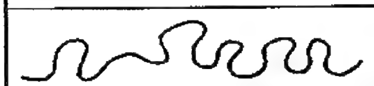
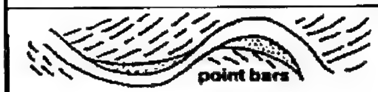
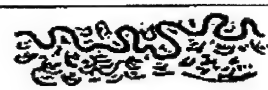
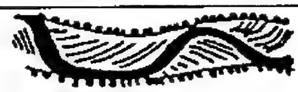
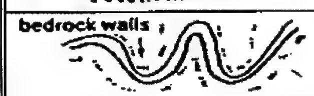
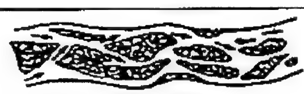
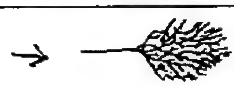
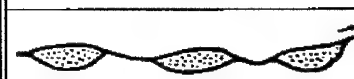
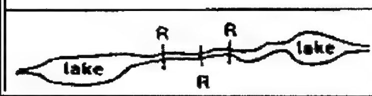
CHANNEL APPEARANCE	CHANNEL TYPE	TYPICAL ENVIRONMENT	TYPICAL BED AND BANK MATERIALS
	(a) Regular serpentine meanders (b) Regular sinuous meanders	Lacustrine plain	Uniform cohesive materials
	Tortuous or contorted meanders, no cutoffs	Misfit stream in glacial spillway channel	Uniform cohesive materials
	Downstream progression	Sand-filled meltwater channel	Slightly cohesive top stratum over sands
	Unconfined meanders with oxbows, scrolled	Sandy to silty deltas and alluvial floodplains	Slightly cohesive top straturm over sands
	Confined meandering	Cohesive top strata over sand substratum in steep-walled trench	Slightly cohesive top stratum over sands
	Entrenched meanders	Hard till or uniform rock	Till, boulders, soft rock
	Meanders within meanders	Underfit streams in large glacial stream spillways	Cohesive materials
	Irregularly sinuous meanders	Thin till over bedrock in plains	Hard and softer materials
	Wandering	Foothills and mountain valleys	Cobble-veneered sand
	Anastomosing	Foothills, plains. Sand bed or gravel paved rivers	Sand and gravel
	Classical braided	Glacial outwash. Foothills	Sand and gravel
	Dichotomic	Alluvial cones and fans	Gravel, sand, silt
	Irregular channel splitting	Large rivers in bedrock	Alternate sand, gravel and rock
	Rectangular channel pattern	Jointed rocks, mostly flat-lying sedimentary rocks	Rock
	Lakes and rapids (R)	Till-veneered Shield terrain	Till, cobbles, boulders, hard rock

Figure 2-11. Some forms of stream planform (after Mollard and Janes 1984)

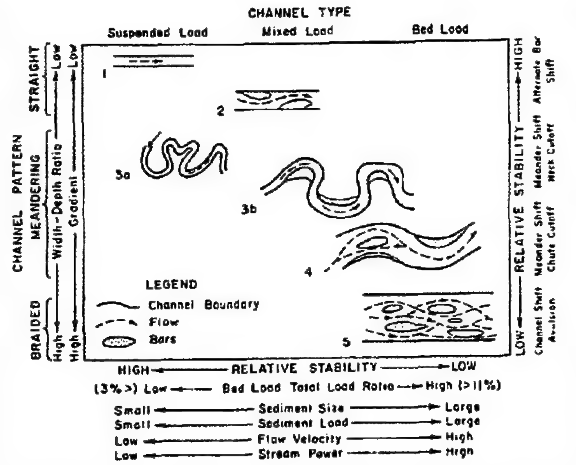
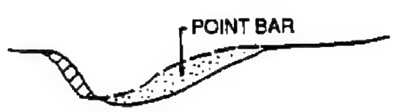


Figure 2-12. Channel classification based on pattern and type of sediment load (Schumm and Meyer 1979, courtesy of Simons, Li & Associates)

(a) Cross-section enlargement by bed scour and bank erosion

(b) Cross-section shrinkage (straight channel) mainly by suspended sediment deposition

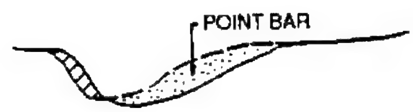


(c) Cross-section shrinkage (meandering channel) by inner bank (point bar) deposition outstripping outer bank erosion

Figure 2-13. Examples of meander shifting and bank erosion (Brice 1984, courtesy of American Society of Civil Engineers)

(a) Cross-section enlargement by bed scour and bank erosion

(b) Cross-section shrinkage (straight channel) mainly by suspended sediment deposition



(c) Cross-section shrinkage (meandering channel) by inner bank (point bar) deposition outstripping outer bank erosion

Figure 2-14. Mechanisms of cross-sectional adjustment to altered inputs of water and sediment

that it is often difficult to enforce such maintenance obligations.

c. Slopes and profiles.

(1) The longitudinal profile of a stream is only partly determined by the landscape. The channel is flatter than the valley slope unless the channel is straight. In many cases, the channel slope represents a long-term equilibrium condition. When a meandering stream is straightened, a steeper non-equilibrium slope is temporarily imposed. Responses in the form of erosion and deposition are then set in motion, in the direction of restoring equilibrium.

(2) The slope of a stream usually flattens gradually from source to mouth. However, local anomalies due to geological controls and other factors are common; for example, the slope will be flatter upstream of a bedrock sill, and steeper below a tributary that delivers quantities

of coarse sediment. Reduction of slope from head to mouth along a stream is related to changes in other characteristics; sometimes changes are relatively abrupt (Figure 2-15).

(3) Processes of channel profile change through time at rates of engineering concern are usually referred to as aggradation and degradation (Figure 2-16). For example, aggradation tends to progress upstream from a dam or grade control structure, and degradation to progress downstream from a structure that traps sediment.

(4) A process referred to as headcutting, common in channelized streams, involves degradation progressing upstream, often accompanied by aggradation progressing downstream. The upstream end of a headcut is called a nick point, or nick zone if it extends some distance along the stream.

d. Bed topography and roughness.

(1) The bed topography and hydraulic roughness of natural channels may vary greatly along the channel and also with stage of flow. The total hydraulic resistance results from a combination of grain roughness and form roughness. Form roughness can arise from bed and bank irregularities and from changes in planform. In active sand channels, bed forms may range from small ripples a few inches in height, to dunes a few feet in height, to larger waves and bars (Figure 2-17). These forms depend on flow conditions and mainly control the hydraulic roughness of the bed. Also, the bed topography at any time depends on the preceding flow history as well as on present conditions. Roughness therefore varies with stage and is not always the same at similar stages - one reason for the looped or erratic stage-discharge curves found in many alluvial streams. Other important sources of form roughness are trees and bushes, river bank protection and structures, floodplain obstructions, bedrock outcrops, bends and scour holes, and abrupt changes in cross section.

(2) Channels formed in coarser sediments have different and often more stable forms of bed topography than sand-bed channels. In gravel-bed streams, the dominant form of bed topography tends to be an alternation of pools and riffles: the pools are characterized by flatter local slopes and finer bed materials, and the riffles by steeper slopes and coarser materials. Bar characteristics and flow resistance in coarse-bed streams are described by various authors (Hey, Bathurst, and Thorne 1982). Armoring, whereby the material on the bed surface is coarser than the underlying material, is described in a related publication (Thorne, Bathurst, and Hey 1987). Some of the features of natural gravel rivers tend to develop in channelized rivers and artificial channels. Armoring is common in regulated streams downstream of storage reservoirs.

(3) When discharges are augmented by flood control works, the prevailing type of bed topography may alter significantly. For example, steep sand streams with high sand transport undergo an abrupt change at a certain flow threshold, whereby the bed forms "wash out" and a more or less flat bed with reduced roughness results (Figure 2-18). This phenomenon tends to reduce flood levels, but to increase velocities with adverse consequences for channel stability. It may cause abrupt anomalies in stage-discharge curves. In some sand-bed channels, bed topography and roughness may also respond to changes in water temperature at a constant flow.

Section II
Principles of Channel Equilibrium and Response

2-4. Basic Concepts

a. The concept that the cross section and slope of a sediment-transporting channel in erodible materials tend to be in a state of equilibrium was developed more or less independently by engineers seeking to design unlined canals that would neither silt nor scour, and by geomorphologists studying the relationship of river channel geometry to hydrologic and environmental factors. The engineering concept was initially expressed by the term regime channel and the geomorphologic concept by the term graded river. Some key quotations are as follows:

(1) When an artificial channel is used to convey silty water, both bed and banks scour and fill, changing depth, gradient and width, until a state of balance is attained at which the channel is said to be in regime (Lindley 1919).

(2) The graded stream is one in which, over a period of years, slope is delicately adjusted to provide, with available discharge and with prevailing channel characteristics, just the velocity required for transportation of the load from the drainage basin (Mackin 1948).

(3) Similar equations (for hydraulic geometry) apply both to rivers and to stable ("regime") irrigation canals which neither scour nor aggrade their beds. The analogy demonstrates that the average river channel-system tends to develop in a way to produce an approximate equilibrium between the channel and the water and sediment it must transport (Leopold and Maddock 1953).

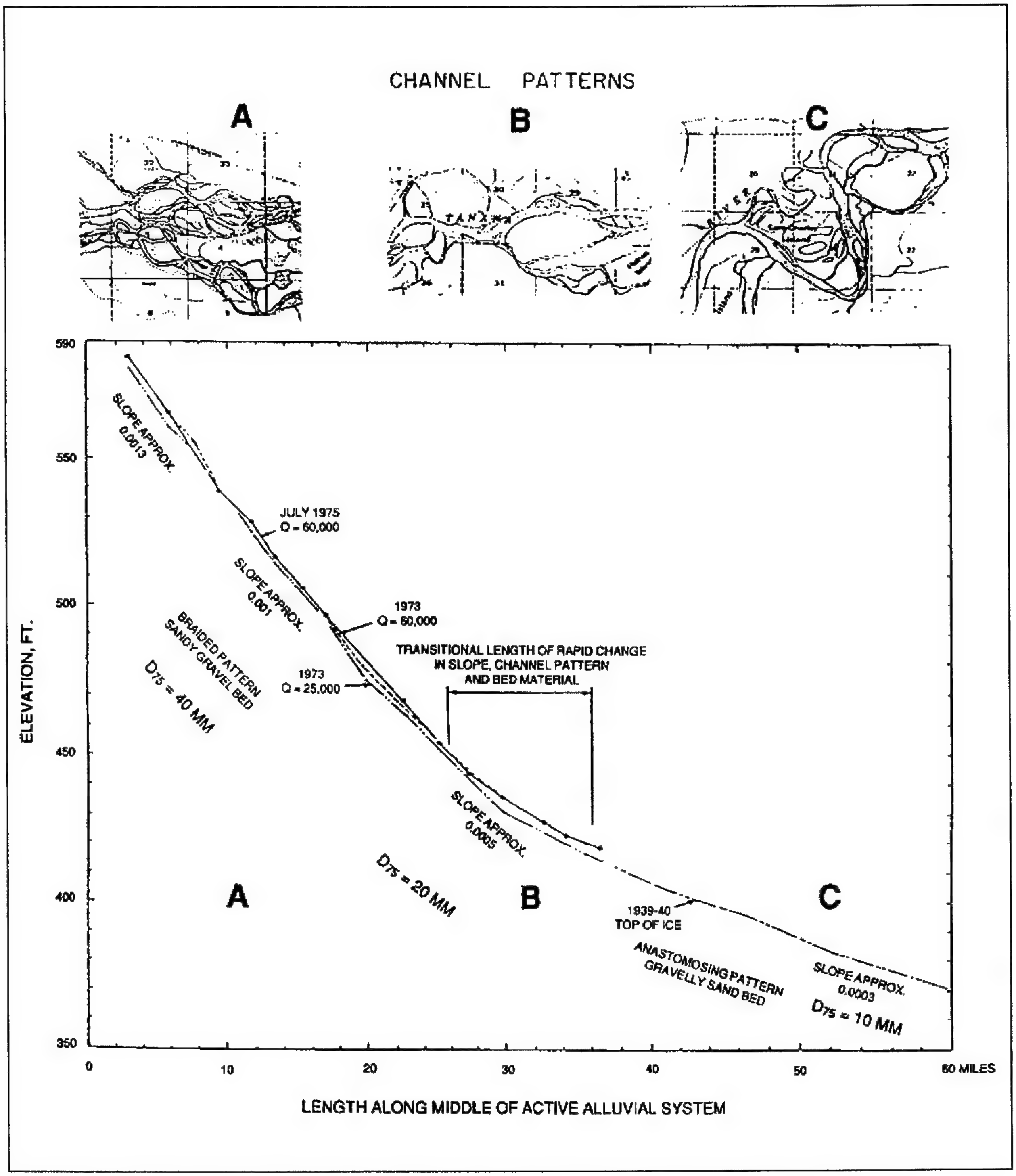


Figure 2-15. Associations between slope, planform, and bed material, Tanana River near Fairbanks, Alaska (from Buska et al. 1984)

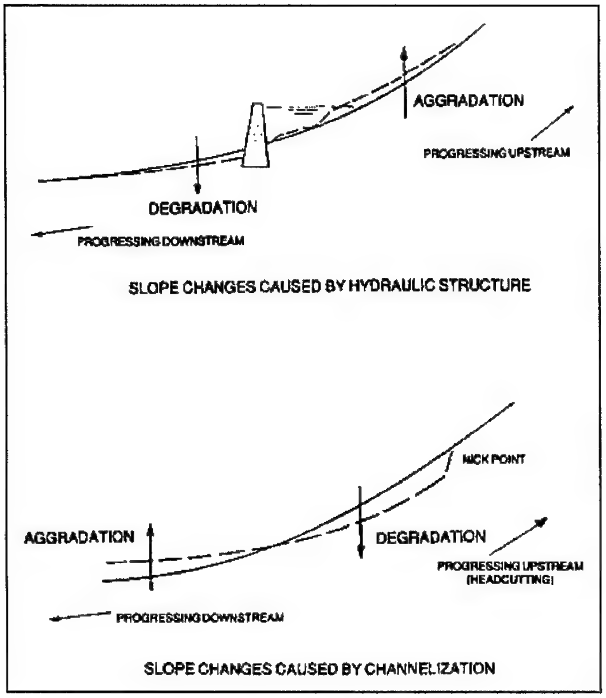


Figure 2-16. Processes of channel slope change

b. The equilibrium or regime concept has been tested against sets of river and canal data from various parts of the world (see Graf 1984, Mahmood and Shen 1971, Nunnally and Shields 1985). Channel widths, depths, and slopes are usually plotted independently against a characteristic discharge. Plots are sometimes stratified according to bed material size or other factors. Curves or equations are fitted and recommended for various analysis and design purposes. The general trend of plots by various investigators is illustrated in Figure 2-19.

c. The regime concept to stability assessment and channel design is essentially empirical. It has been regarded cautiously by many hydraulic engineers because of lack of theoretical verification and sometimes because relationships derived from one region did not fit experience elsewhere. Stevens and Nordin (1987) criticize various aspects of the traditional approach, but conclude: "Lindley's regime concept that an alluvial channel adjusts its width, depth and slope in accordance to the amount of water and the amount and kind of sediment supplied remains unchallenged here. Regime channels are those flowing in their own sediment."

d. Because the term regime has given rise to some confusion and controversy, it will be avoided herein where possible. The concept embodied in the quotations in *a* above will be called the equilibrium concept of channel formation and response. Relationships of channel dimensions and slope to discharge and other parameters will be called hydraulic geometry. The user should be aware, however, that much literature from other countries refers to the regime concept or theory, and to regime relationships, with more or less the same general meanings.

e. The term stable channel has been used extensively in the engineering literature but is also subject to confusion. It is often used to mean a channel that has attained stability of width, depth, and slope. Such a channel, however, may be actively meandering, in which case it is not stable in planform. To avoid confusion, the term is generally avoided in this EM.

2-5. Applicability to Flood Control Projects

a. Reduced to essentials, the equilibrium concept implies that stable width, depth, and slope (and perhaps planform) can be expressed as functions of controlling variables: discharge, boundary materials, and sediment supply (Figure 2-20). Hydraulic geometry relationships may be useful in the planning stages of a flood control project for comparing alternatives and assessing certain stability problems.

b. The concept of degrees of freedom is sometimes useful for visualizing forms of potential instability in erodible channels caused by changes in controlling variables. As a general case, a channel may have at least four degrees of freedom; that is, it can adjust its planform, width, depth, and slope. Other factors such as roughness, bank line shift rates, and sediment transport may also adjust.

c. Some features and difficulties of the equilibrium concept are discussed as follows:

(1) Hydraulic geometry relationships (Figure 2-19) usually deal with width, depth, and slope, but not planform. Stability problems related to planform, for example, whether meanders will develop in an initially straight channel, therefore seem to be outside the scope of traditional equilibrium concepts. Meander geometry is discussed in paragraph 5-9.

(2) Most hydraulic geometry relationships use a single characteristic discharge, intended to be representative of the actual varying discharges, as a primary independent variable. In natural streams this is often taken as the

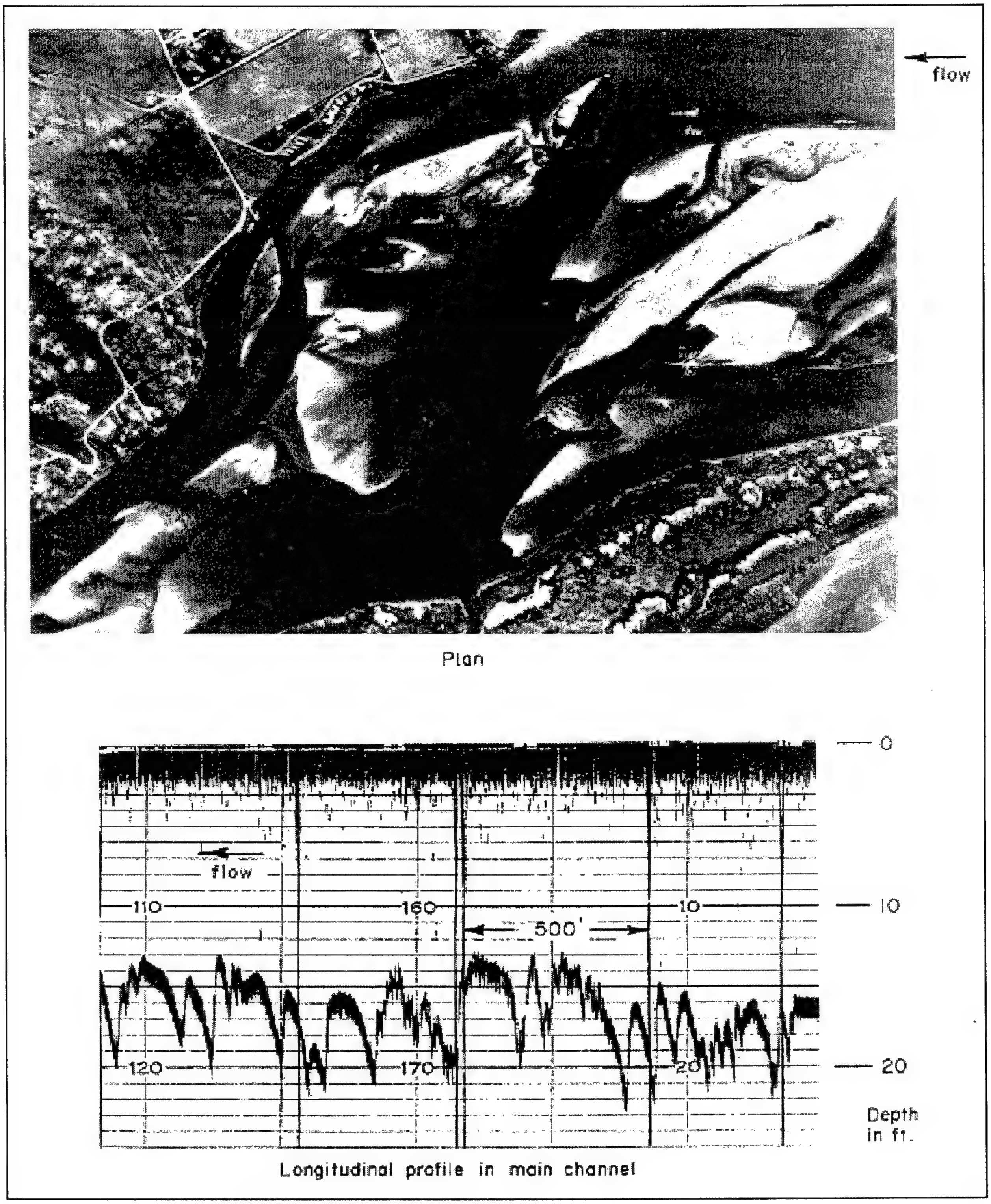


Figure 2-17. Bed forms in sand (Missouri River)

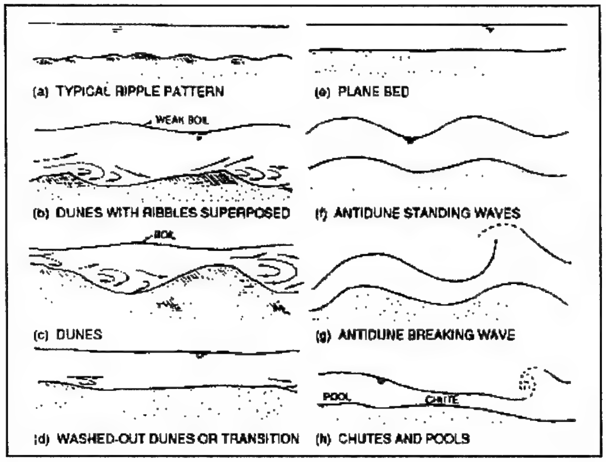


Figure 2-18. Response of bed forms in sand to increasing discharge (a through h) (after Simons and Richardson, 1961)

bank-full discharge, or a more or less equivalent flood-frequency parameter. The terms channel-forming and dominant discharge have been widely used in the literature, and are discussed further in paragraph 2-8.

(3) The primary role of discharge in determining channel cross sections is clearly demonstrated, but there is a lack of consensus about which secondary factors such as sediment loads, native bank materials, and vegetation are significant, particularly with respect to width.

(4) The earlier hydraulic geometry relationships did not explicitly consider sediment transport, and were applicable mainly to channels with relatively low bed material inflows. Equilibrium slopes indicated by such relationships may be too flat to maintain transport of sediment in channels with substantial bed material inflows. Some hydraulic geometry relationships incorporating sediment transport as an input variable have been published (e.g., White, Paris, and Bettess 1981a); but the difficulty remains that at the planning stage of a project, actual sediment inflows are seldom known. Information on assessing sediment inflows can be found in EM 1110-2-4000.

d. A method of applying equilibrium concepts that avoids acceptance of relationships established in unfamiliar or distant environments is to develop local or regional hydraulic geometry relationships for the class of channels of interest. Derived relationships can then be applied to estimate flood control channel dimensions or responses in a particular stream. For example, the consideration of possible width adjustments resulting from augmentation of flood discharges would use a locally developed width-discharge plot rather than a published plot derived from another region. Figure 2-21 shows an example.

2-6. Response of Channels to Altered Conditions

a. Instability and sedimentation have two aspects with respect to flood control channels: the impact of existing processes on the project, and the impact of project changes on the stream system both within and beyond the project length. This section is concerned mainly with the second aspect.

b. If the controlling variables or boundary properties (see Figure 2-20) are altered, the stream or channel will respond by altering cross section, slope, or planform.

c. It is often difficult to determine to what extent observed postproject instability represents a response, or whether it might have occurred in any case as a result of preproject processes. This is especially difficult where the stream has a history of successive modifications from a long-ago natural state. In some cases, long-term

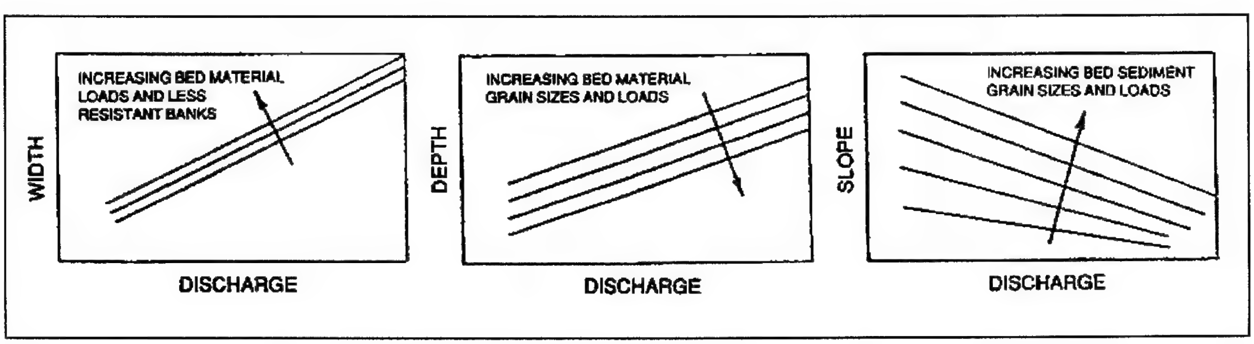


Figure 2-19. General trend of hydraulic geometry plots for channels in erodible materials

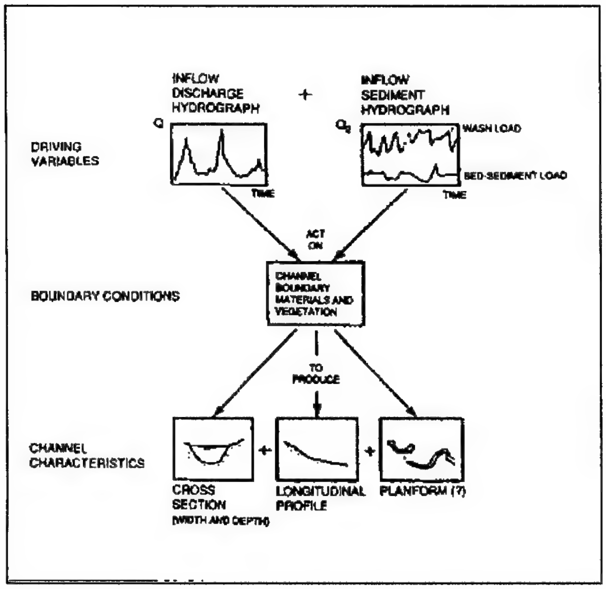


Figure 2-20. Generalized equilibrium concept for long-term formation and response of erodible channels

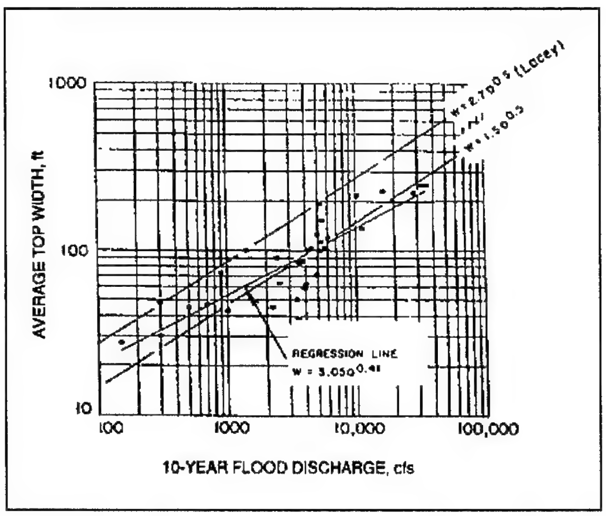


Figure 2-21. Width-discharge plot for specific local set of channels. (Note: 10-year discharge used because of special local circumstances)

responses to a historical sequence of interferences may be extremely difficult to distinguish.

d. Although initial response may occur mainly within the project length, long-term response may affect the stream system far upstream and downstream, including tributaries and distributaries. Where a preproject stability assessment indicates potential problems, stabilization measures such as bank protection, grade control structures, and sediment basins are often incorporated in the design. This will not necessarily eliminate upstream or downstream responses. For example, if a stream has migrating meander bends, stabilizing the bends within the project length may impact on bend migration processes upstream and downstream.

e. Table 2-2 indicates the general direction in which channel characteristics can be expected to respond to changes in driving variables or boundary conditions (see also Figure 2-19).

f. Some additional comments are as follows:

(1) Widths generally vary more or less as the square root of discharges, other things being equal. Widening in response to increased flood discharges can generally be expected. In the case of reduced discharges, ultimate narrowing can be expected if the channel carries enough sediment to deposit on the banks or on side bars.

(2) In the case of meandering planforms, meander wavelength tends to maintain a more or less constant relationship to channel width. Increased flood discharges therefore tend to increase meander wavelength as well as width.

(3) The response of width to changes in bed material inflows is indicated as unclear. Generally, channels with relatively high bed material loads tend to be wider, but a channel with erosion-resistant banks will not necessarily widen in response to increased load.

(4) Depths increase with increasing discharges, but not so much as widths (Figure 2-19). Depths will generally decrease with increased bed material inflow, as slopes increase (see (5) below).

(5) Slopes vary inversely with discharges (Figure 2-19), and tend to reduce by degradation if flood discharges are increased. Slopes tend to increase by aggradation if bed material inflows are increased, and depths reduce correspondingly. Increases in discharge and in bed material input therefore have opposite effects on slope and may largely cancel out if they occur together, for example, as a result of upstream deforestation.

(6) The most widely known geomorphic relationship embodying slope and the equilibrium concept is known as Lane's (1955) principle and can be expressed in the form:

Table 2-2
Expected Response of Channel Characteristics to Changes in Driving Variables or Environmental Conditions (see Figure 2-19)

		Expected Change in Channel Characteristics (Exceptions May Occur)				
Variable Subject to Imposed Change	Nature of Change	Width	Depth	Slope	Platform Type	Bank Erosion
Discharges	Increased	Increased	Increased	Reduced	No marked change	Increased
	Reduced	Reduced or unchanged[1]	Reduced	Increased or unchanged[1]	No marked change	Reduced
Bed-sediment inflows	Increased	Unclear	Reduced	Marked increase	Increased bars and channel splitting	May increase
	Reduced	Unclear	Increased	Reduced	Less channel splitting	May reduce
Bed-sediment grain size	Increased	Insignificant	Reduced	Marked increase	Unclear	Unclear
	Reduced	Insignificant	Increased	May reduce	Unclear	Unclear
Bank conditions	Add bank protection	May reduce	May increase locally	No marked change	As imposed	Reduced locally, may increase downstream
	Removal of woody vegetation	Increased	May reduce	No change	Increased bars	Marked increase

[1] Depending on availability of sediment for deposition.

$$QS \sim Q_s\, D_{50} \tag{2-1}$$

where

Q = discharge, ft³/sec

S = slope, ft/ft

Q_s = bed material discharge, tons/day

D_{50} = median sediment size, ft

This form of relationship indicates that imposed increases in slope lead to an increase in sediment transport assuming the water discharge and sediment size remain constant. If a sinuous channel is straightened, an increased slope is imposed, and increased bed material transport occurs out of the straightened reach, causing degradation upstream and aggradation downstream. The channel thereby attempts to reestablish the original slope.

(7) Channel planform type responds to changes in bed material input if discharges remain unchanged. Generally, increasing bed material loads produces a more disorganized pattern with exposed bars. A densely braided pattern is the extreme example.

(8) Bank erosion and channel shift rates are sensitive to increased in-channel discharges and reduced bank resistance, particularly removal of woody vegetation. (Flood control levees may be an important reason for increased in-channel discharges.)

2-7. Channel Evolution and Geomorphic Thresholds

a. The sequence of responses to certain imposed changes, for example channelization, can be quite complex. An initial profile response may involve temporary aggradation while a later or final condition may involve degradation below original levels (Figure 2-22).

Similarly, bed degradation may undercut high banks and deliver quantities of sediment that temporarily halt or reverse degradation at downstream points. The equilibrium concept generally refers to a supposed final condition following response to a change. In some cases, however, intermediate conditions during the evolution to an eventual equilibrium may be of equal interest.

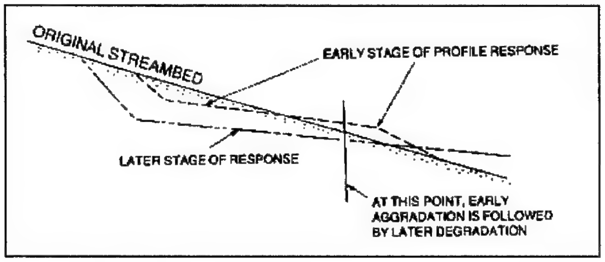


Figure 2-22. Example of complex profile response to channelization

b. Conceptual models of evolutionary response to certain types of channel modification have been developed from field studies. Figure 2-23 shows a scheme developed for incised channels in northern Mississippi, where a complex sequence of responses has occurred as a result of historic basin erosion and sedimentation, past flood control channelization, and alteration of main stem base levels (Schumm, Harvey, and Watson 1984). The model considers cross sections and slopes, but not planforms. The illustrated sequence of cross-sectional types represents a down-channel progression at a point in time, but can also represent time-dependent progression at a point on the channel.

c. Quantitative analysis of response time sequences—for example, profile degradation following reduction of bed material supply—requires use of some form of computational process model. EM 1110-2-4000 should be consulted for information.

d. Some types of response may be initiated quite abruptly when one of the controlling variables passes a certain value. Cases have been described where relatively small changes in climate or land use appear to have triggered large changes in channel characteristics of natural streams. These phenomena are expressed by the concept of geomorphic thresholds (Schumm and Beathard 1976; Ferguson 1984). Reliable data for numerical definition of thresholds appear to be scarce.

e. Various sets of data have been analyzed to discriminate between single and braided channels on the basis of discharge, slope, and in some cases bed material grain size (Leopold, Wolman, and Miller 1964; Ferguson 1984; Struiksma and Kloassen 1988; Kellerhals and Church 1989). These show that for a given bed material and characteristic discharge, braiding is associated with higher slopes. This suggests that if a single channel is subjected to increasing bed material inflows that cause slope to increase, a point will be reached at which braiding develops; however, this may not be possible if the channel is confined by resistant banks. Figure 2-24 shows a composite plot of braiding criteria.

2-8. Hydraulic and Geotechnical Controls

The main driving variables and boundary properties that affect channel characteristics and response are discussed further below (see also Figure 2-20 and Table 2-2):

a. Discharge.

(1) A single discharge value is often used in hydraulic geometry relationships to represent the spectrum of actual discharges. This discharge is sometimes called channel-forming and sometimes dominant. Because "dominant" is sometimes used in a different sense in relation to sediment transport, the term channel-forming will be preferred herein.

(2) In natural streams the channel-forming discharge can often be taken as equivalent to the bank-full discharge. In terms of flood frequency, a return period of around 2 years appears to be common in the eastern half of the United States. In most cases a return period between 1 and 10 years is appropriate. The question of altered channel-forming discharge under project conditions is referred to in paragraph 5-5.

b. Sediment inflows.

(1) Figure 2-20 treats sediment inflows as an external control on channel equilibrium, implying that the sequence of sediment discharges entering the reach of interest is independent of conditions within the reach. Part of the sediment load interchanges with the channel boundaries, and sediment can accumulate within a reach or be augmented by erosion within the reach. Sediment transport within the reach and sediment outflows from the reach are therefore affected by reach processes as well as by inflows.

(2) Sediment in streams can be divided into bed material load and wash load (Figure 2-25). Bed material

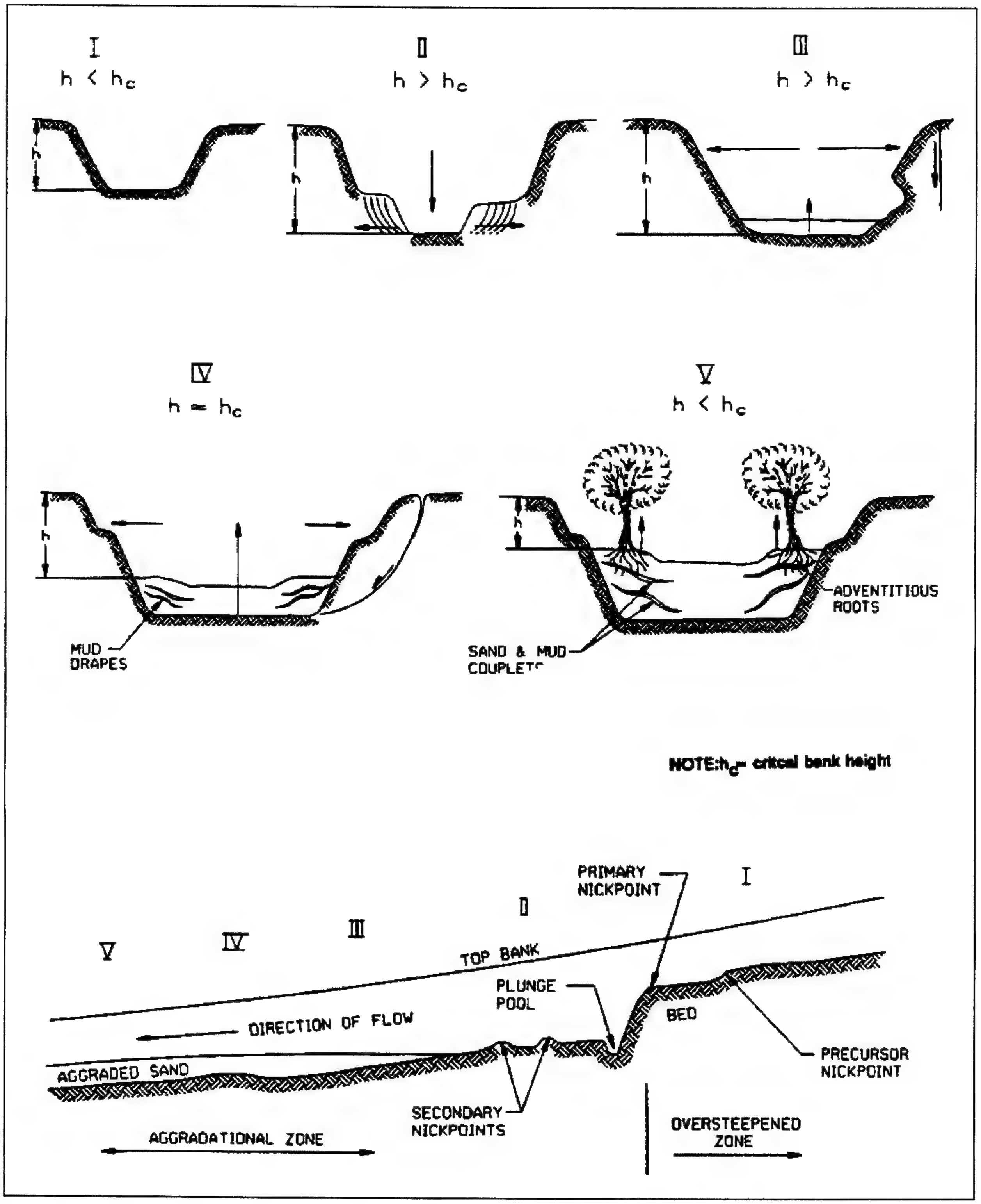


Figure 2-23. Channel evolution model for incised channels (Schumm, Harvey, and Watson 1984, Courtesy of Water Resources Publications)

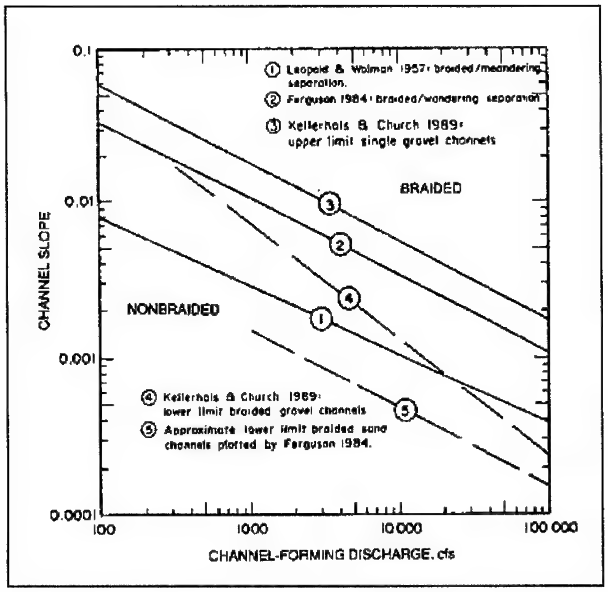


Figure 2-24. Slope-discharge chart distinguishing braided from non-braided channels

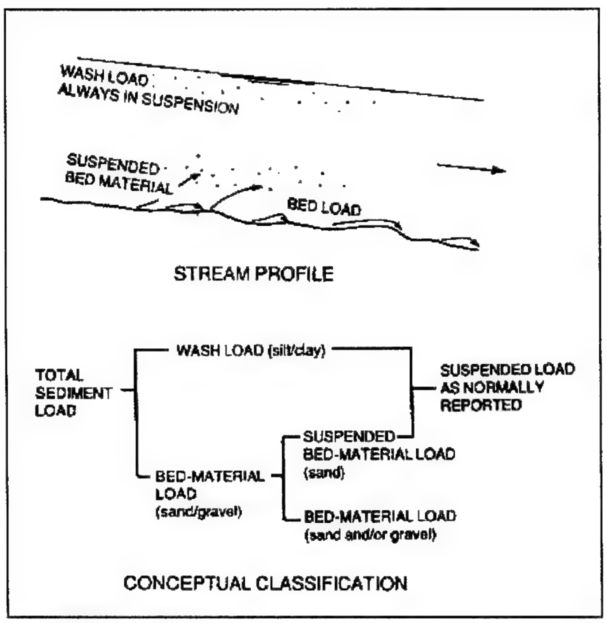


Figure 2-25. Classification of stream sediment loads

load consists of grain sizes found in significant quantities on the bed. It travels either as bed load in contact with the bed or as bed load plus suspended load when velocities are high enough. The rate of bed material transport in both cases is a function of the hydraulic properties of the flow—velocity, depth, and so on. Wash load, on the other hand, consists of finer grain sizes not found on the bed—usually very fine sand, silt, and clay—and is all transported in suspension. Most channels can transport practically all the wash load received from basin erosion, so that the transport rate is determined by supply. Wash load travels through the channel to its destination in a static water body, and does not interchange significantly with the streambed.

(3) Bed material load has an important influence on channel slope, planform, and cross section, as indicated by Table 2-2. Generally, increased bed material load tends to reduce channel stability, because it forms local deposits that divert flow against banks and so on. Increased wash load, on the other hand, may increase bank stability, because it deposits silt and clay on banks during flood recessions, which tends to increase erosion resistance and promote vegetation growth.

(4) Equation 2-2 is useful for qualitative prediction of channel response to natural or imposed changes in a river system. For example, in considering short-term response to a sudden increase in slope—as from channel straightening, and assuming the water discharge and bed material particle size remain constant, the bed material sediment discharge will increase, i.e.,

$$Q_s^- \, D_{50}^0 \sim Q_s^0 \, S^- \qquad (2\text{-}2)$$

The superscript ^{0} indicates no change. Thus, if the slope increases, denoted by S^+, then for the relationship to remain balanced, the sediment discharge Q_s must also increase as denoted by Q_s^+. In the long term, however, the slope will adjust to the long-term bed material input from the basin.

c. Bed material size.

(1) The grain size distribution of channel bed material is often characterized by D_{50}, the median size by weight. This simplification is acceptable for materials with a unimodal grain size distribution of modest range. It may be misleading for very widely graded materials, particularly for sand-gravel mixtures with a bimodal distribution where the computed D_{50} size may be almost absent.

(2) Figure 2-26a shows grain size distributions of bed material and measured bed load in a sand/gravel river. Because material in the coarse sand and fine gravel

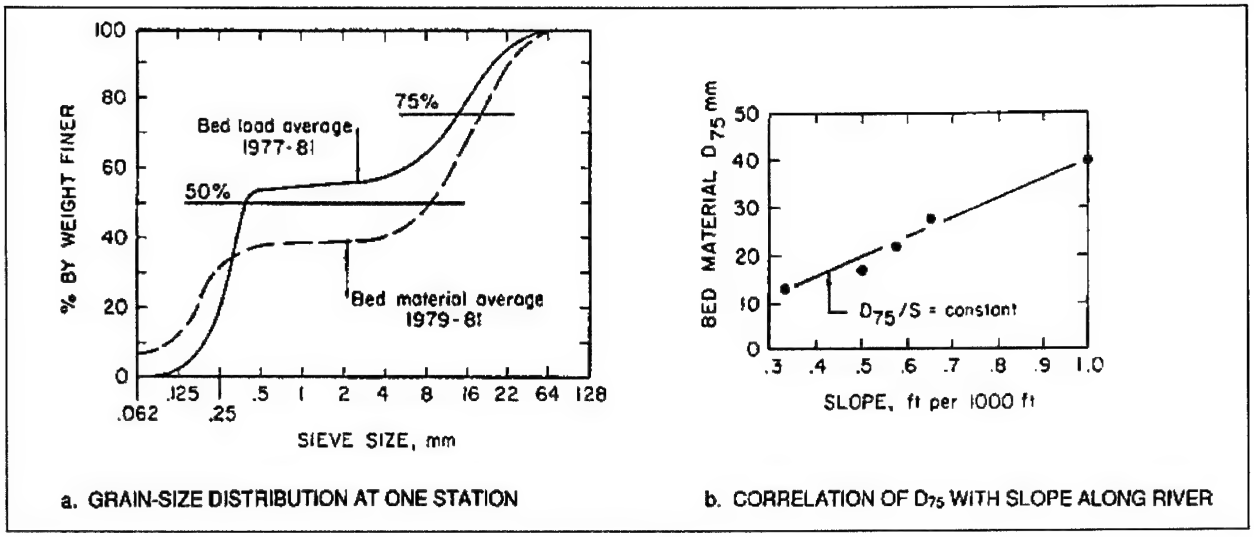


Figure 2-26. Bed material grain size distributions and correlation with slope (Tanana River near Fairbanks, Alaska) (from Buska et al. 1984).

categories is virtually absent, the two distributions show D_{50} values of 8 mm and 0.4 mm, respectively, which greatly exaggerate the overall difference. When the D_{75} size, which falls clearly into the gravel range, was used to represent the bed material distribution, a good correlation was obtained with slope variation along the river (Figure 2-26b).

(3) The channel characteristic most sensitive to bed material size is slope. For example, channels in coarse gravel and fine sand, respectively, equal in terms of channel-forming discharges and sediment inflows, might have slopes differing by more than one order of magnitude. The coarser and steeper channel would also have smaller depths and higher velocities. The influence of bed material size on widths is relatively small and difficult to separate from other factors.

d. Bank materials and vegetation. These factors may affect channel width, planform stability, and rates of channel migration.

(1) For fully alluvial streams flowing within an envelope of self-deposited sediments, it is debatable whether bank materials should be considered as independent factors affecting channel characteristics (Figure 2-20). Vegetation, however, is more clearly an independent factor. Instability is often triggered by the clearing of vegetation from streambanks, and sometimes by eroded and deadfall vegetation within the channel. The role of bank vegetation varies greatly with the region and type of vegetation. Vegetation established on bars during low-flow periods can have a significant effect on channel capacity and processes. Vegetation has been treated as a variable in some hydraulic geometry relationships (Hey and Thorne 1986).

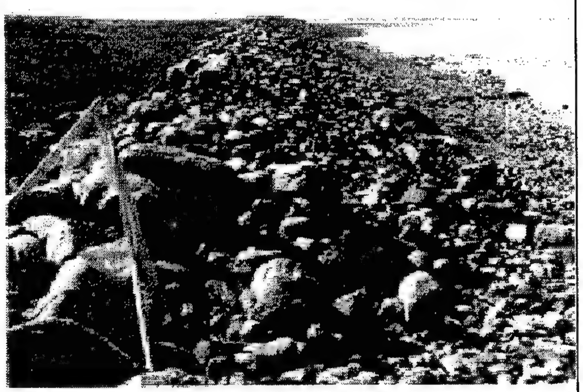
(2) Many erodible stream channels are bounded wholly or partly by clay, compacted silt and loess, glacial till, or glaciofluvial deposits laid down in earlier geological periods. Although channel widths in such cases are often similar to those of alluvial streams, responses to imposed changes tend to be slower. Analogy with similar cases in the region of interest is the best guide to predicting response.

(3) The effect of geotechnical bank stability on channel characteristics is important in some environments. River engineers have tended to regard bank instability more as a consequence than a cause of channel instability, the reasoning being that collapse of the upper bank is initiated by hydraulic scour at the toe. Geotechnical mechanisms, however, appear to be significant primary causes of alluvial bank failures within certain large drainage basins. Hagerty (1992) discusses sequences of alluvial bank failure and erosion of failed soil along streams and rivers. According to Thorne and Osman (1988), bank stability characteristics affect hydraulic geometry in both straight and meandering channels. This topic is discussed further in paragraph 5-9.

e. Ice and frozen ground.

(1) The influence of floating ice on channel characteristics and stability is relatively small except where the ice season is a large part of the year and the largest flows occur during ice breakup, as in Alaska and northern Canada. Channel characteristics in far northern regions include ice-formed features like boulder ridges and paving (Figure 2-27a), and peculiar forms of channel planform resulting from ice jamming.

(2) The direct erosive action of ice on riverbank materials is generally small compared to that of flowing water, but ice easily removes vegetation up to the normal level of ice breakup (Figure 2-27b). Ice blockages can concentrate flows and cause bank erosion and bed scour at certain locations.



a. Boulder ridge

b. Vegetation trim line

Figure 2-27. Ice effects on banks of northern rivers

(3) With regard to frozen ground, Gatto (1984) states: "The effect of permafrost on erodibility is perhaps the factor about which there is most debate.... Some investigators report that ice-rich permafrost increases bank recession.... Other investigators conclude that frozen sediments are harder to erode...." It therefore appears that frozen ground may accelerate or retard bank erosion, depending on the nature of the frozen sediments and the content of pure ice. Hydraulic geometry in cold regions does not appear to be greatly different from elsewhere, but frozen banks may exhibit unusual forms of erosion (Figure 2-28).

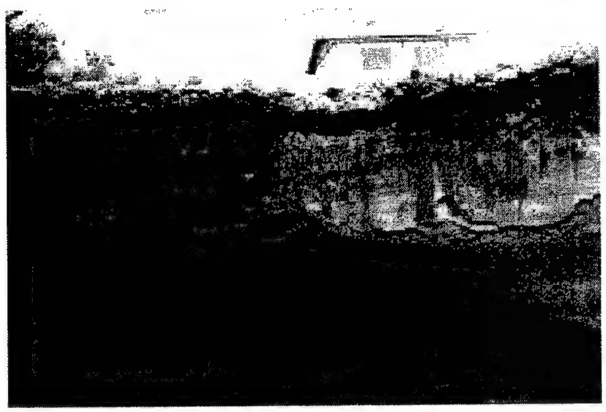


Figure 2-28. Undercut bank erosion in frozen fine-grained alluvium (Kuskokwim River, Alaska)

Chapter 3
Stability Problems with Flood Control Channels

Section I
Types of Channel Modification for Flood Control

3-1. General

a. There are many methods of channel modification that may be used to increase channel capacity and thereby provide flood control benefits. The local environment and the desired degree of capacity increase affect the choice of method. Generally, urban areas require more intense investigation than rural areas due to congested developments. Stability and environmental sensitivity must be considered when evaluating alternatives.

b. Because of stability and ecological problems that have arisen in many projects, modification of natural channels to provide increased flood capacity has come under increasing attack as an automatic response to flooding problems. Before radical channel modification, consideration should be given to the potential benefits of offstream storage for avoiding or reducing ecological and stability problems. In many basins, natural storage on floodplains has been reduced by agricultural or urban developments and by flood control projects, leading to an increase in flood peaks and severity of flooding and to loss of ecological habitat. Creation of offstream storage basins can reverse this trend, and appears to be a favored policy in parts of Europe (Mosonyi 1983; Schiller 1983; Schultz 1987).

c. General methods of channel modification available for consideration include clearing and snagging, cleanout, channel enlargement, channel realignment, levees, floodways, and flow diversions. These are discussed separately in subsequent paragraphs.

3-2. Clearing and Snagging

a. This method is normally used when the channel is restricted by extensive vegetative growth, accumulation of drift and debris, or blockage by leaning or uprooted trees; and when only a modest increase in hydraulic capacity is required and can be obtained through reduction in channel roughness. The procedure involves removal of log jams, large trees spanning the channel, sediment blockages, underbrush, and miscellaneous debris (Figure 3-1). It is generally advisable to avoid disturbing large stable trees on the banks (larger than 12 in. diam at breast height), as well as all species of special environmental value. Clearing and snagging reduces hydraulic roughness, in some cases increases cross-sectional area, and reduces potential for further blockages and hang-ups of drift. Regular maintenance must be carried out to ensure continued satisfactory operation.

Figure 3-1. Clearing and snagging

b. Potential stability and sedimentation responses to clearing and snagging are associated mainly with increased velocities and with removal of vegetation that may have acted locally as erosion protection. Effects on stability may be adverse in some places and beneficial in others. Local experience is generally the best guide.

c. Retention of tree canopy is usually beneficial to fish and wildlife. Increased light due to reduction in canopy can encourage growth of silt-retaining reeds and willows, which can rapidly neutralize the hydraulic benefits of clearing and snagging.

d. Clearing and snagging is also discussed in paragraph 6-8*b*(2). For further details see Nunnally and Shields (1985) and EM 1110-2-1205.

3-3. Cleanout

Channel cleanout normally involves removal of a specified thickness of material (usually 1 to 3 ft) around the wetted perimeter of a channel. This method is used when a relatively small increase in capacity is required but cannot be obtained by clearing and snagging. Channel cleanout is also discussed in paragraph 6-8*b*(3). Potential stability and sedimentation responses to cleanout are similar to those for channel enlargement, as discussed in paragraph 3-4.

3-4. Enlargement

a. Channel enlargement is normally used when hydraulic capacity must be significantly increased (Figure 3-2). Examples include a channel through a formerly rural area that has undergone suburban or urban development, or the upgrading of an urban channel to carry a 100-year flood or of a rural channel designed to minimize flood damages on crops and residences. Modes of enlargement include increased bottom width, flattening of side slopes by excavation, channel deepening, side berm cuts, or a combination of two or more of those.

Figure 3-2. Channel enlargement

b. The extent of enlargement is determined by the desired reduction in flood levels consistent with permissible disturbance of rights of way considering the relationship with the environment and the requirements for maintenance.

c. Channel enlargement poses two major potential problems with respect to stability and sediment deposition. Firstly, if depths are increased but the original slope is retained, the bed and banks may erode, especially if bank stability previously depended on cohesive sediment deposits, armoring, or vegetation that was removed in the enlargement process. It may be necessary to provide artificial drop structures to check the velocities. Secondly, if the channel carries substantial sediment loads and if the cross section provided to meet flood control needs is too large (see paragraphs 2-4 through 2-8), the section may partly infill with sediment deposits and the calculated flood capacity may not be achieved without maintenance.

d. A method of enlargement that can reduce instability problems is the use of side berm cuts to form a two-stage channel (Figure 3-3). This type of cross section consumes more land than simple enlargement but is more effective for conveying bed material, because higher velocities are maintained at moderate discharges. The preferred arrangement is with the cut on the inside bank as illustrated. In incised channels, the level of the berms should, if possible, correspond to the channel-forming discharge under modified conditions (see paragraph 2-8). (Nunnally and Shields (1985) refer to this form of cross section as a "highflow channel" and suggest that the berm should correspond to mean annual flood.)

3-5. Realignment

a. Realignment of meandering streams was widely used in the past as a flood control measure to increase hydraulic capacity and to reduce loss of land by meander migration. The realignment sometimes took the form of complete replacement of a meandering length by a straight channel, or alternatively, the elimination of selected meander bends by "cutoffs" (Figure 3-4). The increased capacity results partly from increased slope and partly from reduced eddy losses and roughness.

b. The response of a stream to realignment can vary greatly depending on the stream characteristics and the environment. In some environments, streams with stable contorted meanders, flat slopes, and erosion-resistant boundaries can be considerably realigned without serious consequences (Figure 3-5), especially if there are flood-regulating reservoirs. In other environments, straightening of meandering streams to enhance flood capacity has led to serious problems of channel degradation, bank erosion, and tributary incision (Figure 3-6). In such cases realignment may be viable only if accompanied by grade control structures to check velocities and bank protection to control development of new meanders.

3-6. Levees

a. Levees or embankments are often provided to protect floodplain property, without modifications of the channel itself. A case for levees in place of more radical methods is stated by Ackers (1972) as follows: "the present width and gradient of the river, if it is indeed stable, are the regime values. Consequently, any attempt to make a significant alteration to the cross section may be thwarted by a redistribution of sediment. It is preferable therefore to retain the regime width and slope, up to the level of the dominant discharge, and to provide the increased flood capacity by berms, and flood banks [levees] perhaps, that only come into effect at discharges with a frequency less than the dominant condition."

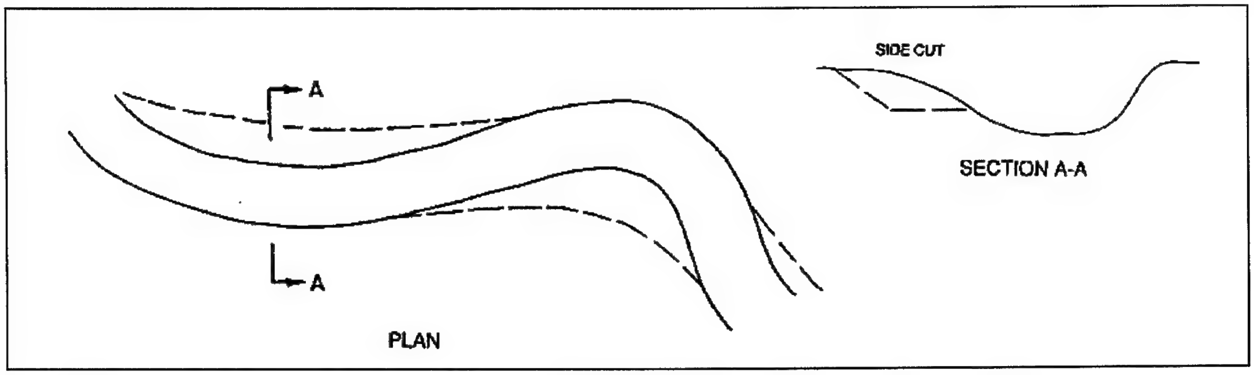


Figure 3-3. Channel enlargement by side berm cut

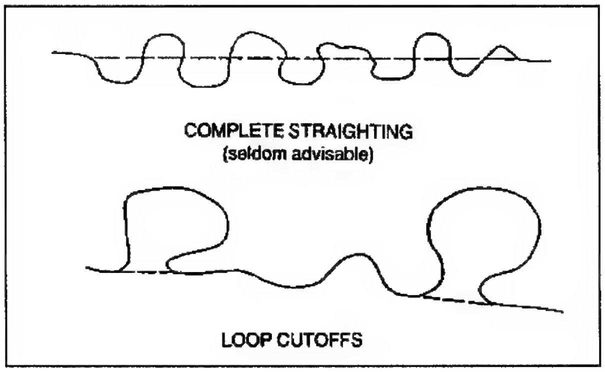


Figure 3-4. Forms of channel realignment

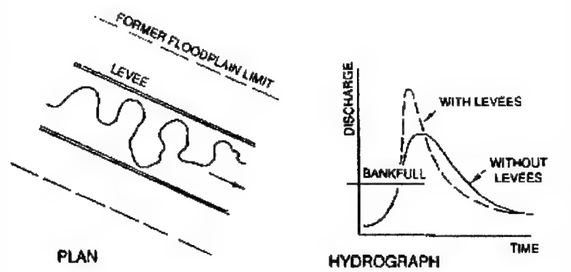
Figure 3-5. Realigned channel without serious instability problems

b. Levees are not, however, free from potential instability effects. Unless they are set far back from the channel banks, they may cause increased flood peaks in

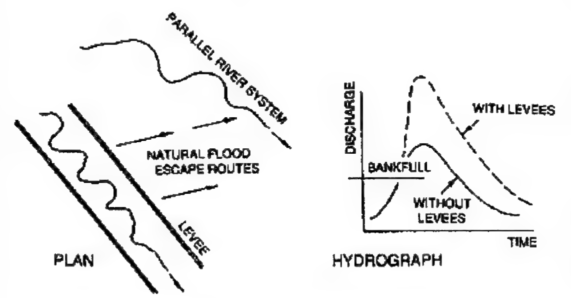
Figure 3-6. Lateral instabillity in realigned channel

the channel proper because floodplain storage and conveyance are reduced (Figure 3-7a). This concentrates a higher proportion of flood flows within the channel, tending to initiate channel widening and lengthening of the meander bends. The discharge-increasing effect of levees may be more pronounced in flat deltaic regions where under natural conditions, overbank flows may escape completely from the channel under consideration to reach the terminal water body by other routes (Figure 3-7b). In such cases the levees not only eliminate floodplain conveyance and storage, but prevent the escape flows. Long levee projects in such situations may lead to complete reforming of meander patterns and to slope flattening by upstream degradation and downstream aggradation.

c. Levees may also cause sediment deposition in streams with high sediment loads by restricting transport and deposition of sand on overbank areas. More sand is then retained in the channel to deposit farther downstream



a. Effect of reducing floodplain storage and conveyance (flood volume unchanged)



b. Effect of blocking escape routes (flood volume increased)

Figure 3-7. Effects of levees on flood hydrographs

in reaches of flatter slope. This may initiate a progressive upstream-advancing aggradation of the bed. Also, thick deposition of finer suspended sediment on the berm between the riverbank and the levee (occurring mainly during flood recessions) may overload the bank, causing slump failures.

d. In actively meandering channels, the danger exists that continued meander migration, perhaps aggravated by increased in-channel discharges, will encroach on levee setback distances and attack the levee itself at various points. If populations depend on the levees for security, this may pose a critical situation in large floods. As time passes, levee projects in this type of situation tend to require ever-increasing vigilance and maintenance. Eventually large portions of the stream may be effectively canalized by bank protection of one form or another (Figure 3-8).

3-7. Flood Bypass Channels

a. A flood bypass channel is usually completely separate from the existing channel whose capacity it is designed to supplement. In some cases the two channels may intersect at intervals as in the case of high-level bend cutoffs (Figure 3-9).

Figure 3-8. Bank protection necessitated by encroachment on levee setback

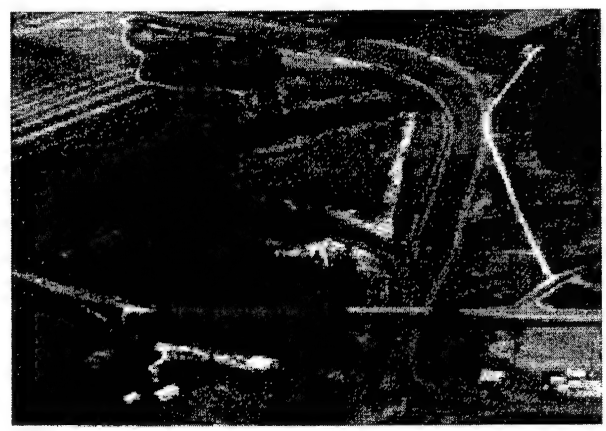


Figure 3-9. Flood bypass channel formed by high-level bend cutoffs

b. The most appropriate application of bypass channels is usually for streams with relatively low bed material loads. In other cases they may cause sediment problems if the division of sediment between the original channel and the bypass channel does not match the division of flow. Bypass channels should normally be provided with control structures at entrance and exit. A channel may be modified for flood control by diverting flow out of it to another system or into it from another system.

3-8. Flow Diversions

a. When flows are diverted out, erosional problems are normally reduced downstream of the diversion. Sediment deposition may occur in the main channel or in the diversion or in both as the combined sediment-carrying capacity of both is likely to be less than that of the existing channel. The division of sediment between the two channels is not necessarily proportional to the division of flow. Further deposition problems may arise if there are substantial downstream inflows of sediment that the reduced flows are unable to transport.

b. When flood flows are diverted in but the channel is not deliberately modified to accommodate the increased discharges, serious erosional problems may ensue. The channel tends to respond by widening and deepening, and by flattening slope through upstream degradation and downstream aggradation. A spectacular example is illustrated in paragraph 3-16.

Section II
Case Examples of Stability Problems

A number of cases of channel instability in flood control projects are summarized to illustrate the range of problems that can be encountered. All these cases have been investigated or analyzed to some degree; but a full diagnosis of the problems is not always possible, especially where the stream or channel in question has a history of previous interventions. Cases are drawn from several regions of the United States and involve various types of channels.

3-9. Twenty Mile Creek

a. Twenty Mile Creek is a tributary of the Tombigbee River in mixed woodland and farmland in northeast Mississippi. The creek flows through easily erodible sandy-silty alluvial deposits underlain by clay at variable depths, typical of streams in northern Mississippi. Most of the creek was apparently cleared and straightened to some extent by local agencies at various periods between 1910 and 1940, but it was probably not substantially enlarged at that period. A length of 12 miles upstream from the mouth was channelized by the U.S. Army Corps of Engineers between 1965 and 1967: the lower 9 miles was widened and deepened and the upper 3 miles was cleared and snagged. The combined effect was to increase the average cross-sectional area by about 200 percent, the slope by 50 percent, and velocities by 50 percent or more. The magnitude of flood peaks at given return periods increased greatly, partly because the enlarged channel captured flood runoff that had previously flowed overland, and partly because of increasing intensity of agricultural land use in the basin.

b. Instability response to the project was rapid and extensive. The main changes documented up to 1982 were as follows:

(1) The channel widened substantially over a large part of the project length, especially by increase of bed widths (Figure 3-10). As-constructed side slopes of 1V:3H steepened substantially by toe erosion.

(2) The longitudinal slope flattened substantially over the project length by bed aggradation at the lower end and degradation at the upper end (Figure 3-10). Bed material deposited at the lower end was derived from widening and meandering farther upstream. Dredging was required near the mouth to maintain channel capacity.

(3) The bed degraded by headcutting, the channel widened, and meanders developed over a length of stream extending at least 7 miles upstream of the head of the project (Figure 3-11).

(4) Headcutting was initiated in several tributaries as water levels in Twenty Mile Creek were reduced by the enlarged cross sections and bed degradation.

Remedial measures were applied to check the instability. Grade control structures were installed at several points on Twenty Mile Creek and on several tributaries. Riprapping and planting of vegetation was done for bank protection.

3-10. Puerco River

a. The Puerco River is an ephemeral stream in arid uplands in northwest New Mexico. The history of response to historical land use and climatic changes is somewhat obscure, but there is evidence of substantial regional changes in channel characteristics after the introduction of cattle around 1880. Some reaches of the channel are deeply entrenched (Figure 3-12); others are not. The plan and profile are constrained locally by rock ridges, but the channel has mostly a flat, smooth bed of fine to medium sand. The natural banks are mostly of stratified fine sand and silt with occasional layers of cemented sand and gravel. Floods are extremely flashy, lasting 24 hr or less, but carry very high concentrations of sand and silt. The bed is active only during a few flood events each year.

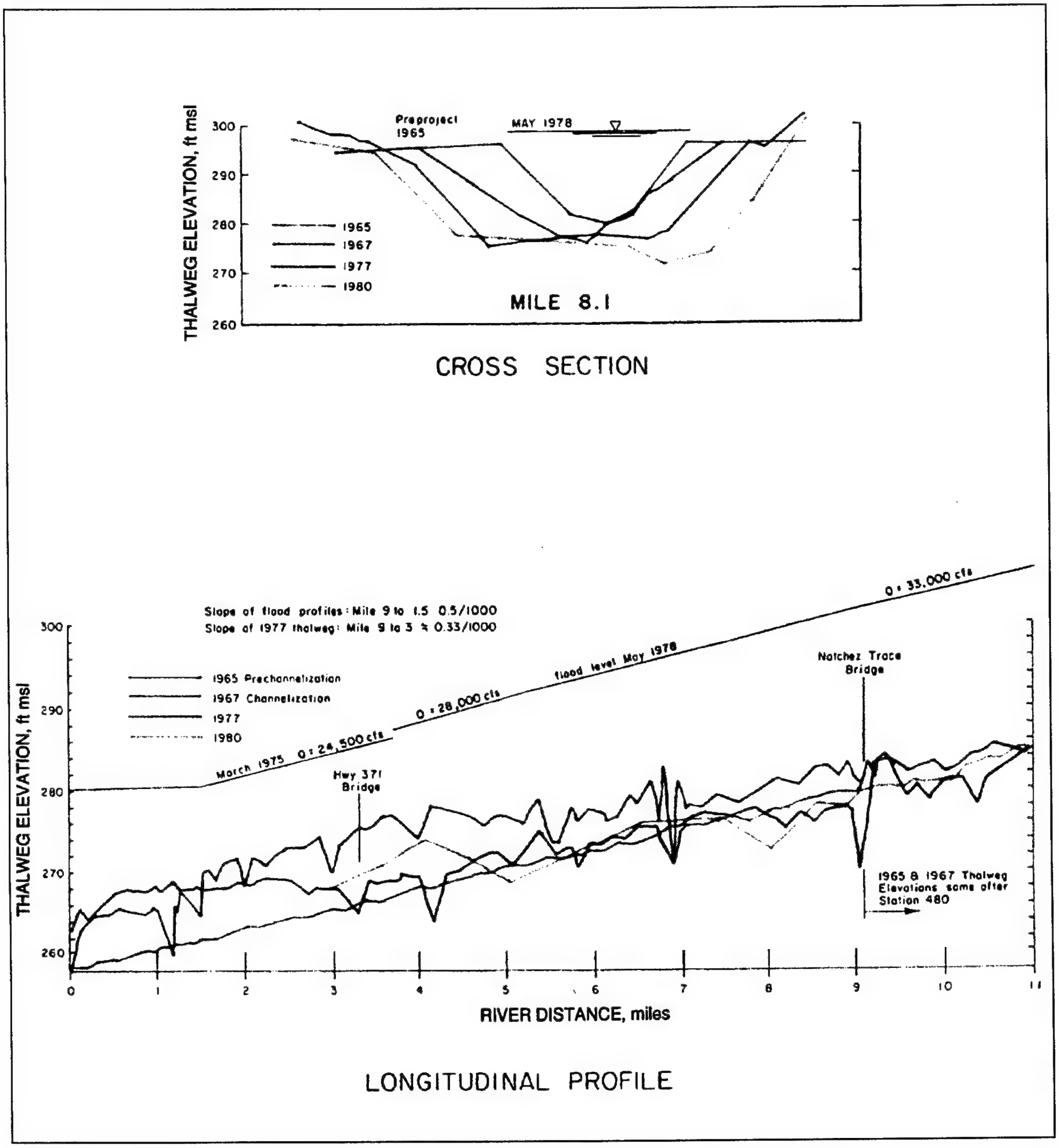


Figure 3-10. Cross-section and profile responses to channel enlargement, Twenty Mile Creek

b. Various works have been constructed to control the channel through the town and reduce flooding of urban land. Two lengths each about 2 miles long were channelized in the 1970's in connection with an interstate highway project. The main features and responses were as follows:

Figure 3-11. Induced instability upstream of channel enlargement, Twenty Mile Creek

Figure 3-12. Entrenched reach of Puerco River

(1) Upper channelization. The channel was straightened and shortened rather severely. Channelized cross sections appear on average considerably wider than natural sections. Limited bank protection using jacks was installed, and the excess slope was partly compensated by installing grade control structures. The main response seems to be a trend to resumption of a meandering pattern.

(2) Lower channelization. The river was fixed in a sinuous planform using concrete side slopes. The width provided was about 50 percent greater than the natural width. The main response seems to have been deposition of sand and a consequent rise of 3 to 5 ft in bed levels. Clearance under bridges was seriously reduced (see Figure 5-12).

c. Analysis of the instability problems of the Puerco River is hampered by incomplete information and by the special characteristics of ephemeral arid-land channels with high sediment inflows. In the lower channelization, the enlarged channel appears unable to transport all the inflowing sand, presumably because of lowered velocities. The observed aggradation might, however, be caused in part by a deficiency of larger floods. This cannot be checked because of lack of reliable streamflow data.

3-11. Grapevine Spillway Channel

a. Grapevine Lake is a flood control, water supply, and conservation reservoir on Denton Creek northwest of Dallas, Texas, completed in 1952. The spillway, designed for a Probable Maximum Flood flow of nearly 200,000 cubic feet per second (cfs), discharges into what was originally a small creek. A moderate spillway discharge episode in 1981, the first major overtopping since construction, lasted about 3 weeks with a peak flow of about 10,000 cfs. This episode produced dramatic enlargement and downcutting of the creek channel over a 3,000-ft length (Figure 3-13). The erosion is partly into silty-sandy overburden but extends well down into a horizontally bedded shale or sandstone that is apparently highly susceptible to disintegration by weathering and to hydraulic erosion.

Figure 3-13. Grapevine Spillway Channel after erosional episode

b. The main point demonstrated by this case is the potential for extremely rapid enlargement and downcutting, even in partly consolidated materials, when a

channel is subjected to flows grossly in excess of the channel-forming discharge. The damaging flows exceeded the channel-forming discharge of the creek by one to two orders of magnitude.

c. Rehabilitation involved construction of a $10 million concrete chute and stilling basin to carry flows from the end of the existing spillway slab down to the new base level of the creek.

3-12. Snake River

a. The Snake River near Jackson Hole in western Wyoming is a braided gravel river in a wide floodplain (Figure 3-14). Bed material transport is moderately high. Upstream of the town of Jackson, the active braided system is bounded by flood control levees built in the 1960's. Downstream of Jackson, there is an intermittent system of short levees and other flood protection works. The total length of river wholly or partly protected is about 25 miles. The main instability problem (as of 1987) was the heavy cost of emergency maintenance of the existing system during and after flood events: the river continuously shifted the location and orientation of its main channel and attacked the levees at new points. Damage to existing riprap protection is usually caused by the main flow impinging more or less at right angles against the banks and undermining the toe as it turns abruptly and produces a deep scour hole. Heavy driftwood and tree trunks add to the force of the attack. Original riprap protection seemed to be deficient in size and thickness and especially in toe protection.

Figure 3-14. Snake River near Jackson Hole

b. The main form of instability exhibited by the Snake River is an irregular and more or less unpredictable shifting of the main channel during floods. This type of shifting is characteristic of active braided rivers.

3-13. Little Tallahatchie River

a. The Little Tallahatchie River is a meandering sand-bed tributary to the Yazoo River basin in north-central Mississippi, discharging to a leveed floodway in the Mississippi/Yazoo floodplain (Biedenharn 1984).

b. About 85 percent of its drainage area is controlled by Sardis Dam, constructed in 1939 for flood control and located about 22 miles above the present mouth. A certain amount of channel improvement was done downstream of the dam in the form of clearing and snagging and cutoff of a few meander bends. As a result of the dam, downstream flood discharges were greatly reduced: whereas predam floods had frequently exceeded 20,000 cfs, postdam floods were generally limited to 6,500 cfs, more or less the bank-full capacity of the channel (see Figure 2-9 in Chapter 2).

c. The initial instability response of the river below the dam was slope flattening by downstream-progressing degradation, resulting from trapping of the bed material load in the reservoir. This is a typical response downstream of reservoirs that trap bed material (see Table 2-1). As a result of the combined effects of smaller flood discharges and bed degradation, the water levels at the mouths of tributary streams were substantially lowered, so that the tributaries were "rejuvenated" by augmentation of their hydraulic gradients. Bed degradation started progressing up the tributaries, followed by bank failures and meandering; and quantities of coarse sand and gravel bed material were delivered to the Little Tallahatchie Channel. The reduced flows in the Little Tallahatchie were unable to transport all of this material; therefore, as a secondary response to the project, the channel started to aggrade, except for a 3-mile reach immediately below the dam (Figure 3-15).

d. As a result of this complex response, dredging has been required on the Little Tallahatchie Channel to maintain flood capacity and flood control benefits, and erosion protection and grade controls have been required on several tributaries to reduce loss of land and delivery of coarse sediment. The case demonstrates how initial and final instability responses may operate in opposite directions, and how tributaries may degrade when main stem flood levels are lowered by flood control.

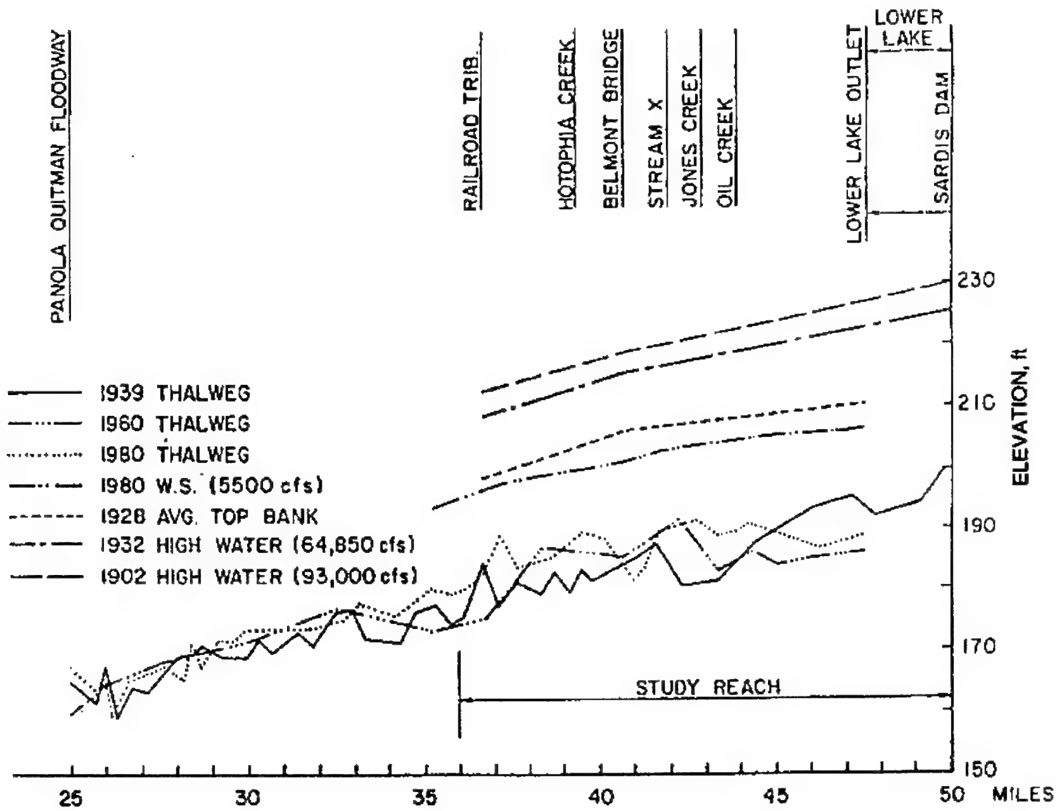


Figure 3-15. Response of Little Tallahatchie River profile to upstream reservoir

3-14. Red River

a. The Red River, one of the major streams in the southern United States, has its source in New Mexico and flows generally east along the Texas-Oklahoma border and through Arkansas to join the Atchafalaya River in east-central Louisiana. The Red River is a dynamic river, continually shifting its planform through bank caving and meandering (Figure 3-16). The sediment load is relatively high.

b. A historical phenomenon that affected the river system was the formation and subsequent removal in the mid-19th century of a huge series of log jams called the Great Red River Raft, which at its greatest extent covered a length of about 160 miles in Louisiana. The raft was removed in 1873, and further accumulations were cleared periodically. The river has been affected in more recent times by various works for flood control and navigation. Nearly 60 percent of its drainage area is controlled by Dennison Dam, located about 500 miles above the mouth and constructed in 1943. Base levels at the mouth have been lowered by channel improvements on the Atchafalaya and Lower Mississippi Rivers, and the river itself has been trained and shortened in various places for flood control and navigation.

Figure 3-16. Red River

c. The combined response to all these developments includes a marked incision of the lower river, such that a 50-year flood is now contained within banks in many places, and widening of the channel by a factor of up to 2 or 3. The incision is illustrated by Figure 3-17, which shows "specific gauges" at Shreveport in western Louisiana over the period 1890-1986.

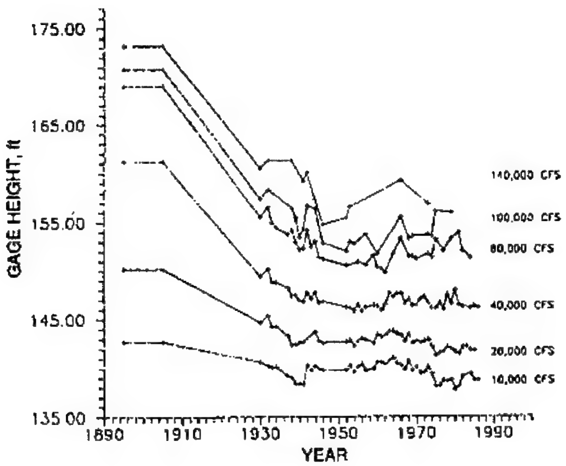


Figure 3-17. Specific gauge plot for Red River at Shreveport, Louisiana, over period 1982-1986. Datum for gauge height is mean sea level

d. The Red River case illustrates the difficulty of sorting out responses to a series of historical events and developments. For example, it is not immediately clear to what extent the incision illustrated in Figure 3-17 represents a response to removal of the log raft or to subsequent base level lowering. There is no evident response to construction of Dennison Dam in 1943.

3-15. Sacramento River

a. The Sacramento River flows south through over 200 miles in the Central Valley of California. It is a meandering sand-bed river in its lower part but has a significant content of gravel bed material in its middle and upper reaches. It is regulated by Shasta Dam in its upper reaches and affected by irrigation diversions and bypass floodways in the lower valley. Considerable lengths are bordered by flood protection levees that follow the margins of the meander belt. Historically, the river was greatly disturbed by hydraulic mining operations in the mid-19th century. This supplied large quantities of coarse sediment to the river and caused aggradation of up to 30 ft in certain reaches. This temporary slug of sediment has by now largely worked through the system.

b. Recent studies show no systematic trend of changes in the longitudinal profile. Rates of bank erosion apparently reduced by about 25 percent after construction of Shasta Dam in 1943, but remain troublesome for security of the levees and loss of valuable agricultural land. Various methods have been tried for bank protection in response to environmental concerns over use of riprap, but success with alternative systems has been limited (Figure 3-18).

c. The main instability problem affecting flood control works on the Sacramento River is bank erosion associated with systematic shifting of meanders. This is essentially a continuation of predevelopment trends, and there is no evidence of aggravation by recent developments. Bank attack could be reduced by further storage regulation to reduce flood peaks and bed material loads. In the absence of such measures, there is little alternative but to focus on bank protection.

3-16. Long Creek Basin

a. Long Creek near Oxford in northern Mississippi is a tributary of the Yocona River, which since 1953 has been regulated by Enid Dam located about 7 miles upstream of the mouth of Long Creek. Like many other basins in the Yazoo Basin uplands east of the Mississippi Valley, Long Creek basin was devastated by exploitative cotton agriculture in the mid-19th century. Many of the present stream channels have cut through "post-settlement alluvium:" this valleywide deposit is derived from severe hillslope and sheet erosion during the early cotton period. The post-settlement alluvium and the underlying older alluvial and lacustrine deposits are generally very susceptible to hydraulic erosion.

b. The recent history of basin changes, in-stream works, and instability responses is complex. Starting in the 1930's, considerable lengths of stream channel were straightened and rechannelized for flood control. Base levels were lowered by regulation of the Yocona River and also by flood control in the Mississippi Valley. Some reforestation and soil conservation have been done in the upper watershed, and some land has reverted from cultivation to woodland. Grade control structures and lengths of bank protection have been installed in parts of the watershed to arrest bed degradation (incision) and bank erosion.

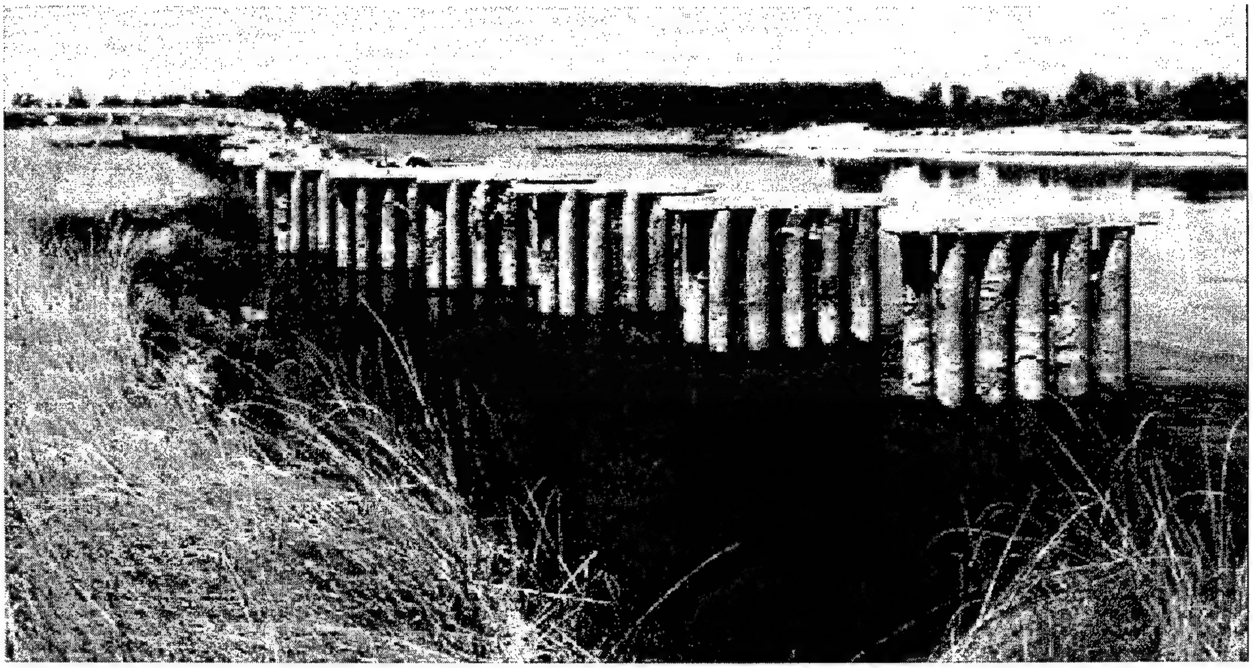


Figure 3-18. Flanking of experimental bank protection on Sacramento River

c. The main instability responses to 20th century developments appear to be a general incision that has advanced to the middle and upper parts of the basin by upstream migration of nick zones (Figure 3-19), and re-formation of meanders in reaches that had been straightened for flood control. The incision process has been checked by installation of grade control structures, or in some cases by road culverts. The meander development has been checked by provision of various forms of bank protection. Experience with Long Creek and similar basins in Mississippi shows the potential for widespread channel incision when base levels are lowered in areas of highly erodible soils. Incision is followed by bank failures, channel widening, and transport of sediments to downstream locations of deposition.

3-17. Tanana River

a. The Tanana River is a tributary of the Yukon River, which rises in the Alaska Range in central Alaska and forms the south boundary to the city of Fairbanks. Upstream of Fairbanks, it is an active braided river with a gravel bed. Some distance downstream, it changes to a more or less meandering river with a sand bed. In the vicinity of Fairbanks it displays a transitional planform consisting of several channels with large semistable islands (Figure 2-15).

b. Flood control works were constructed in the 1970's to protect Fairbanks. The Chena River tributary, which passes through the city, was controlled with a dam and floodway so that flood flows are diverted to the Tanana upstream of the city. A setback levee was built along the right floodplain for a distance of approximately 20 miles, with occasional groins to resist specific threatened encroachments by the river. At the downstream end of the levee, it was found necessary to build the levee out into the river because no land was available between recently eroded riverbanks and valuable existing developments. This in-river length of the levee was provided with several long groins that project out into the river to deflect the main flow away from the levee (Figure 3-20). The in-river construction was a matter of local controversy and generated public concerns, but was eventually approved and implemented.

c. The main observed response of the river to the flood control project was from the in-river construction. During construction a pilot channel had been excavated to encourage the river into a new channel outward of the groins (Figure 3-20). Alluvial material from the pilot channel excavation, instead of being removed, was stockpiled alongside. In the following high-water season the river removed most of this material, plus additional

Figure 3-19. Incised channel in Long Creek basin

material eroded from the pilot channel area, and deposited much of it downstream in the form of new channel bars. Dredging was required initially to safeguard navigational access to the mouth of the Chena River, but the problem more or less resolved itself over subsequent seasons.

d. Prior to and contemporaneous with the flood control project, other developments interfered with natural evolution of the river to some extent. These were mostly connected with gravel extraction from midriver islands and associated access roads. One access road that closed off a minor channel probably triggered rapid shifting of a sharp main-channel bend. It was this shifting that more or less forced in-river construction of the downstream end of the levee.

Section III
Causes and Forms of Instability

3-18. General

a. The information provided in this section is intended to supplement more general information on channel response contained in Chapter 2, as well as case examples described in Section II. Extensive information on past problems is contained in a Congressional record on stream channelization (U.S. Congress 1971). A nationwide inventory of flood control channels (McCarley et al. 1990) indicated that bank instability and channel siltation were the most common stability problems. Table 3-1 summarizes common potential problems associated with various types of channel modification.

b. Although the following discussions focus on individual causes and forms of instability, these seldom occur singly. It may be very difficult to determine the exact causes of an observed complex pattern of instability, or to forecast exactly what forms can be expected from a specific project proposal.

3-19. Continuation of Pre-existing Processes, e.g., Meandering

a. In many cases an existing channel to be used for flood control will already display instability, which may be aggravated under postproject conditions. Probably the

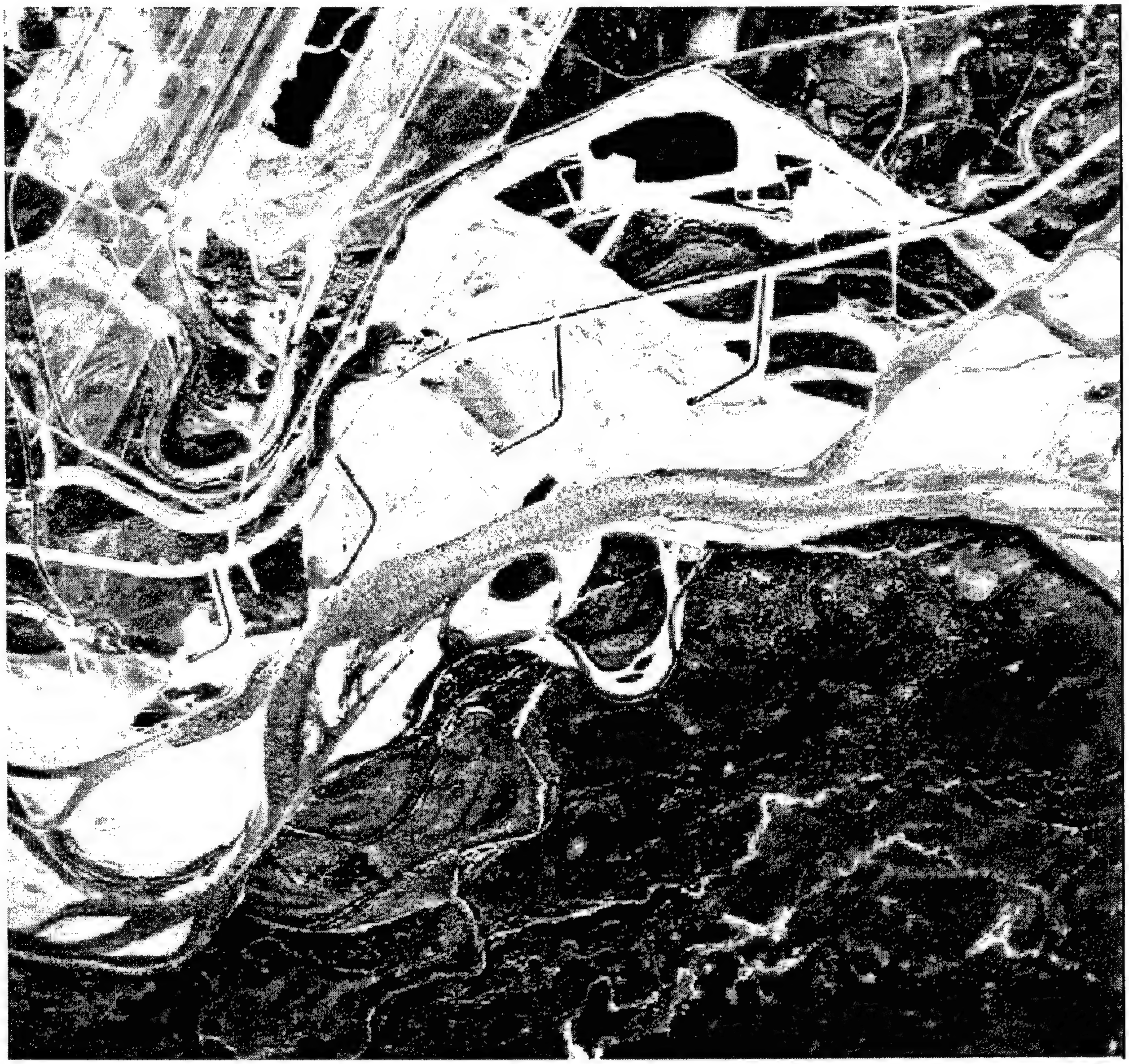


Figure 3-20. Tanana River at Fairbanks showing in-river levee and groins

most common form of instability is meander migration, which if untreated may impact on project levees. Meandering is discussed at length in a conference proceedings (Elliott 1984). Following are some significant points:

(1) Although erosion tends to occur along outer concave banks and deposition along inner convex banks, this can reverse at certain locations under certain forms of meandering.

(2) Meanders can start in straight channels as a result of side bar deposition from bed material transport (Figure 3-21), but the question of whether bed material transport is necessary for initiation of meanders is unsettled. Meander development and migration involve sediment exchange between eroding and depositing locations (Figure 3-22).

Table 3-1
Potential Stability Problems from Flood Control Modifications

	Potential Stability Problems		
Forms of Channel Modification	Within Reach Directly Affected	Upstream	Downstream
Clearing and snagging	Bank erosion and bed scour	Headcutting	Sedimentation
Cleanout or enlargement	Bank erosion; sedimentation	Headcutting	-
Realignment	Bank erosion and bed scour; meandering	Headcutting	Sedimentation
Levees	Meander encroachment on setback	-	Increased flood peaks
Floodways and bypasses	Sedimentation of original channel	-	-
Diversions out	-	-	Sedimentation
Diversions in	-	-	Bank erosion and bed scour
Base level lowering (parent stream)	-	Bed scour, widening, tributary degradation	-
Storage reservoir or sediment basin	-	Delta formation; aggradation	Bed degradation

Figure 3-21. Side bar deposition and sub-meandering in straight channel

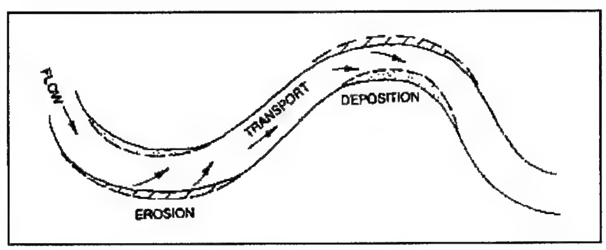


Figure 3-22. Sediment transport associated with shifting of meander bends

(3) Initial meander development is often self-reinforcing because the generated sediment transport tends to feed the process. It is easier to check at an incipient stage than later.

(4) Analytical prediction of whether a straight channel will start meandering is seldom practicable. It is better to rely on related local experience and to conduct post-project monitoring.

(5) Design of sinuous rather than straight channels is frequently advocated on environmental grounds (Keller and Brookes 1984, Rechard and Schaefer 1984; Nunnally and Shields 1985). It is sometimes claimed that

meandering channels can be more stable, but quantitative guidance is lacking.

b. The braiding form of instability (see also paragraph 2-3) occurs naturally in channels with relatively high slopes and bed material loads, but may be induced by a flood control project. In a case reported by Gregory (1984), a meandering channel widened and braided after the effective slope was increased by flood control measures.

3-20. Increased Discharges

a. Various basin developments and project features such as deforestation, urbanization, channelization, and diversions may increase inflow discharges of given frequencies. Increased discharges tend to cause cross-section enlargement, accelerated meander migration and eventual lengthening of meanders, and longitudinal profile changes. If profile changes include upstream incision, in-channel flood discharges may continue to increase after project completion.

b. In general, increased discharges tend to cause an eventual flattening of slope through upstream degradation (otherwise described as incision or headcutting) and downstream deposition. Such changes may be masked in the short term by the complexity of erosional and depositional responses and by other project changes such as straightening. Degradation and the longitudinal response of channelized streams are discussed in detail by Galay (1983), Schumm, Harvey, and Watson (1984), and Neill and Yaremko (1988). Incision tends to be most severe with fine bed materials; in coarser materials with a wider range of sizes, it is often limited by armoring. Longitudinal profile response can be studied using the one-dimensional computer program HEC-6 (U.S. Hydrologic Engineering Center 1993): see EM 1110-2-4000 for further guidance.

c. Cross sections and their response are discussed in paragraphs 2-3 and 2-6. In general, increased discharges tend to cause widening and deepening. Some additional points about cross-sectional stability are as follows:

(1) Severe cross-sectional changes may follow longitudinal incision as banks are undercut. The section may go through a complex cycle of changes (Schumm, Harvey, and Watson 1984; Thorne 1988).

(2) Provision of a very wide section does not necessarily ensure bank stability. An inner meandering channel may form and attack the banks.

(3) Narrow, deep channels, which may appear attractive for hydraulic conveyance, are maintainable in erodible materials only with very flat slopes and low velocities. In nature, they are found mainly in very fine grained or organic materials with very low bed material loads.

3-21. Realignment and Channel Improvement

a. Straightening in past projects was designed to increase hydraulic conveyance and sometimes to reduce loss of land by bend erosion. However, unless grade control structures are used, which tend to negate the hydraulic advantage, straightening may have severe effects on channel stability, resulting in greatly increased sediment loads with downstream siltation and deposition and loss of fishery habitat. Although bank erosion and meander migration may be relieved temporarily, many straightened channels tend to revert to a meandering state unless bank protection is provided.

b. Modifications such as clearing and snagging and cleanout (usually employed in relatively small channels) often entail some removal of vegetation and reduction of roughness. This tends to increase velocities while reducing erosional resistance, and may increase bank erosion and sediment transport unless the operations are carefully planned, conducted, and monitored.

3-22. Flow Regulation by Reservoirs

a. Upstream effects of a reservoir include delta formation, gradual raising of stream levels in the backwater zone, and more pronounced meandering.

b. Downstream effects result from altered outflows and retention of sediment. The purpose and mode of operation, and the degree of control over runoff at the reach of interest determine the magnitude of the flow effects. Reservoirs usually reduce downstream flood flows and increase low flows (Figure 3-23). Such changes tend to improve stability in the main stream, but tributaries may be destabilized because of lower water levels at their mouths - as in the case described in paragraph 3-13.

c. Storage reservoirs generally capture all the incoming bed load and a high proportion of the suspended load (Figure 3-24). The downstream channel profile tends to degrade in the form of a wedge starting at the dam (Figure 3-25). Theoretically this process continues indefinitely, but in practice a near-equilibrium condition is

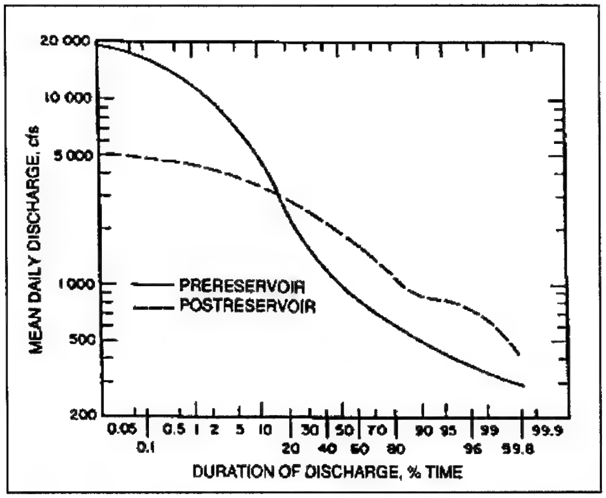


Figure 3-23. Effect of storage reservoir on downstream flow-duration curve

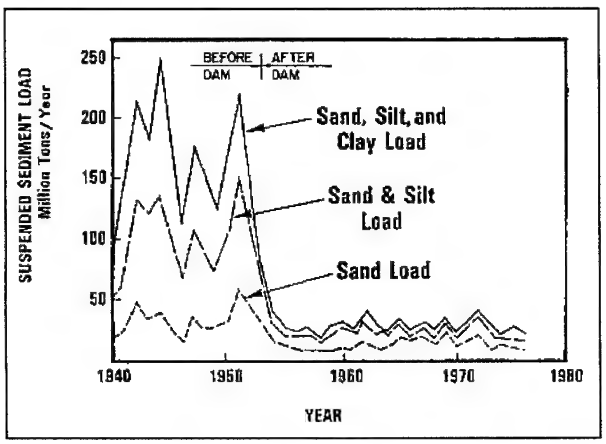


Figure 3-24. Effect of storage reservoir on downstream sediment transport (Missouri River average annual suspended sediment load at Omaha, Nebraska)

eventually attained after a time and distance that differ widely from case to case. In the North Canadian River below Canton Dam, Oklahoma, the distance was more than 100 miles and possibly up to 300 miles (Williams and Wolman 1984). As in the case of upstream incision, downstream degradation tends to be deepest in fine material and to be limited by armoring in coarser materials.

d. Reduced flood peaks and reduced bed material load may have partly compensating effects on the downstream channel. If the flood peak reduction is great enough, degradation may be insignificant. The profile

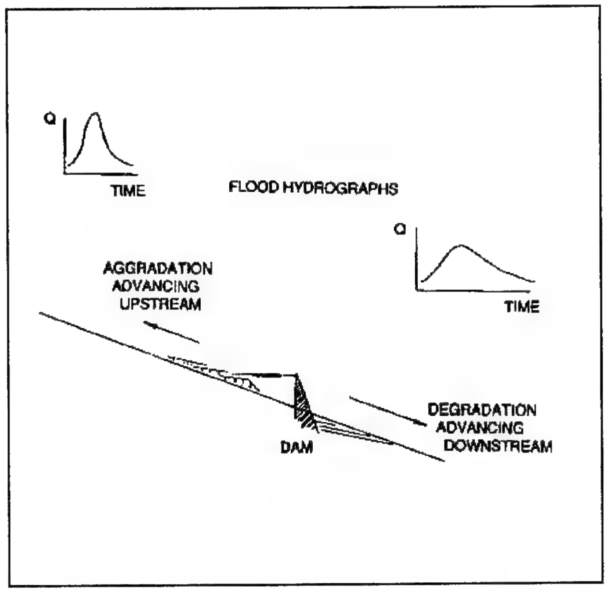


Figure 3-25. Effects of storage reservoir on profile stability.

effects of altered hydrology and sediment supply can be studied using HEC-6 (U.S. Hydrologic Engineering Center 1993).

e. Downstream effects on channel widths are variable. Studies of 17 cases found widening in 50 percent of cross sections, narrowing in 25 percent, and no change in 25 percent (Williams and Wolman 1984).

f. In some cases the effects of storage reservoirs may be opposite to those implied above. If bank-full discharges are released for longer durations than occurred in the natural stream, bank erosion may be aggravated. If bed material inflows from downstream tributaries are high relative to those captured by the reservoir, the downstream channel may actually aggrade because the reduced flood peaks are unable to transport the inflows.

3-23. Sediment Transport and Channel Stability

a. Sediment transport can be both a cause and a result of instability. Bed material load and wash load have different effects on stability: increasing bed material transport tends to increase instability, but heavy wash loads of fine material may promote stability by depositing cohesive layers on banks and encouraging vegetation. Contrary to popular belief, bank erosion associated with meander migration does not necessarily cause high sediment loads, if erosion on one bank is balanced by deposition on the other, as in lowland floodplains.

b. The designed slope and cross section for a project channel must be capable of maintaining transport of incoming bed material; otherwise deposition and loss of hydraulic conveyance will occur.

Chapter 4
Assembly of Information for Stability Evaluation

4-1. General

a. Evaluation of channel stability (see Chapter 5) requires assembly of relevant information on the channel and drainage basin. This chapter provides guidance on collection and assembly of information. Many of the information items may also be required for other project purposes, such as hydraulic and geotechnical design and environmental assessment.

b. Guidance is provided below under a number of headings, corresponding more or less to separate steps appropriate to a project of substantial scope. In the case of small projects, information assembly may be consolidated in accordance with the time and resources available.

4-2. Review of Historical Developments

a. In assessing an existing stream system, it is important to identify historical developments that may have affected its morphology and stability. In some areas the present characteristics of many streams are partly a result of past developments and interferences. Documentary on historical alterations may be difficult to find. However, comparisons of historical maps and of ground and aerial photographs can provide clues as to when significant changes occurred. It may then be possible to obtain information on what actually happened to cause the changes.

b. Historical information is needed for the project stream itself and also for the upstream basin. Large-scale changes in land use often affect channel stability by altering runoff, drainage conditions, and sediment supply. Information on major historical floods predating gage records is often useful. Past diversions into or out of the stream for flood control, irrigation, or other purposes may be key factors. Repairs and modifications to bridge crossings and other river structures may be significant.

c. Information can be summarized in the form of a brief calendar of the most significant administrative, social, and technical changes known to have occurred. An example is shown in Table 4-1. Suggested sources of historical information are listed in Table 4-2. See also Appendix E of EM 1110-2-4000.

Table 4-1
Example of Historical Development Calendar

Date	Development	Agency
1880-1900	Agricultural settlement: conversion from forest to farmland	--
1907	Extreme flood (not measured): extensive damage to farms and communities	--
1910-1925	Channelization and straightening of parts of stream system	Local drainage district
1934-1938	Construction of few soil conservation dams in upper basin	Soil Conservation Service
1955	Hydraulic study followed by limited dredging and bank protection work over lower 10 miles of main stream	Corps of Engineers
1950-1970	General intensification of agricultural development	--
1967	Highest gaged flood	U.S. Geological Survey
1972	Flood control study with recommendations for channel improvements	Corps of Engineers
1977	Environmental study: recommended halt to channel improvement plans	U.S. Environmental Protection Agency

Table 4-2
Suggested Sources of Historical Information

Previous studies and reports: Corps of Engineers, Soil Conservation Service, U.S. Bureau of Reclamation, consultants, etc.
U.S. Geological Survey Quadrangle Sheets: old and new series
Aerial photographs: for some areas AAA photos from the 1920's are available
Topographic maps by Army Map Service and others
County maps and city plots
Offices of county, state, highway, and railroad engineers
Local newspapers
Older inhabitants, especially farmers
U.S. Geological Survey: gauge histories and descriptions, gauging notes, rating curves through period of record; water supply papers; provisional discharge records
National Weather Service: storm and flood records
Municipal water and power plants: gauge records
Irrigation and drainage districts: gauge records

4-3. Map and Aerial Photo Interpretation

a. Topographic maps of various scales can indicate the nature of the drainage basin and stream system, the planform of the channel and its relation to the floodplain, and such physiographic controls as valley walls and intersecting ridges. Maps of different dates can sometimes be used to examine planform changes, and approximate longitudinal profiles and slopes can be developed from contour maps. For smaller streams, however, standard topographic maps may be of limited use.

b. Aerial photographs, stereoscopic if possible, are usually the most practical remote-sensing tool for study of stream channels and their changes (Figure 4-1). They are good for most cases except perhaps smaller streams in heavily wooded terrain. Frequently a number of series dating back to the 1950's or even the 1920's are available. Aerial photos permit examination of sediment deposits and bars, rapids, erosion sites, ice-formed features, and the general characteristics, location, and planform of the channel at various times. Extensive examples of aerial photo interpretation of channel patterns and features can be found in several publications (Mollard and Janes 1984; Cornell University 1952).

c. Quality of photography and suitability of scales may vary greatly between different dates. Low-level, large-scale photographs are not always the best for showing channel features, especially in wooded terrain, because morphologic features tend to be obscured by vegetation, and tone contrasts between different sediments and ground covers tend to be suppressed. For medium-sized streams, scales in the range of 1:10,000 to 1:30,000 are often best. Experienced interpreters generally use a pocket stereoscope for viewing.

d. When aerial photos of different dates are compared, account should be taken of water-level differences, which may be obtainable from hydrometric gage records. Care is also required in horizontal registration of overlays of different dates, with attention to fixed control points and the edge distortion inherent in uncorrected vertical photographs.

e. In a case study in Mississippi, aerial photos of 1986 were compared with presettlement maps of 1830 to examine major changes in channel location that had been initiated by agricultural development and subsequent basinwide erosion and sedimentation. In some reaches the mapped location of the 1830 channel was detectable from stereo viewing of the 1986 photos, being marked by contrasts in vegetation, edges of tree belts, and terrace scarps (Figure 4-2).

f. Satellite imagery, generally available since 1972, is useful for examining basin characteristics and land use changes. The coarse resolution of most early imagery limits its usefulness for channel studies. This limitation has improved dramatically in recent years with 30-meter (m) digital thematic mapper (TM) data and 10-m panchromatic data. With the most recent remote sensing/ Geographic Information System (GIS) software, engineers/scientists can conduct detailed analysis of basin land use changes, point bar formation, bank movement, meander migration, and flood overflow changes, and subsequently compile these data in a structured database that allows for multilevel queries. Imagery, whether it be from a satellite or scanned aerial photography, can be geo-corrected to a particular map projection, resampled to a particular scale, and overlaid in a multiple-layer GIS. The ability to query the database allows study managers to make decisions with a high degree of confidence. Queries may entail computations of linear measurements, area, and land use and visual methods of overlaying layers of the database. Past manual methods of planimetric river analysis can be supplemented or in some cases replaced by remote sensing/GIS technology.

4-4. Field Inspection

a. In the evaluation of the stability of an existing stream and basin, field observation is very important. Field inspection should be done after a review of maps and aerial photos. Further visits may be required at later stages. Both ground and aerial inspections are advisable where possible. Photographs (panoramic where appropriate) and notes or audio records should be taken of all significant features. Photographs should be mounted and annotated to show key features, and numbered for ease of retrieval. Video records may be useful in some cases.

b. Inspection should be done by persons experienced in river hydraulics and stability problems. The main inspection should normally be done under low to moderate flow conditions when the bed and banks of the streams are more easily seen, and preferably when foliage is absent. Additional observations under storm or flood conditions may be appropriate. In cold regions, the main inspection must be done when channels are free of ice and snow, but additional observations under ice conditions may be appropriate.

Figure 4-1. Aerial photograph of meandering river illustrating channel features

c. Electronic means of note taking such as tape recordings are favored by some observers, but they can require a troublesome amount of subsequent processing and interpretation. Excessive photography poses similar problems. Recording of information should be guided by considerations of necessity and sufficiency.

d. Excessive reliance should not be placed on observations from bridge crossings. In many cases, bridges tend to be built at special sites that are not typical of the stream as a whole. Also, bridges may create hydraulic anomalies in the course of time. On the other hand, evidence of extensions, underpinning, and remedial work at bridges may reveal instability problems.

e. The guidance provided here applies particularly to hydrotechnical aspects of stability. Joint inspections with geotechnical and environmental evaluation personnel may offer technical and economic advantages.

4-5. Key Points and Features

Points and features to be particularly looked for in field inspections are listed below under several heads. For background on the significance of points listed, reference should be made to Chapter 2, particularly paragraphs 2-3 and 2-8. The list does not necessarily include all features that may be significant in a particular case. Table 4-3 provides a summary checklist. If the channel has been subject to past works and interferences, efforts should be made during the field inspection to detect response in the form of changes to cross sections, slopes, planform, channel shifting, sedimentation, etc.

a. Upstream basin conditions.

(1) Topography, soils, vegetation, land use, and ongoing changes that may impact on channel stability.

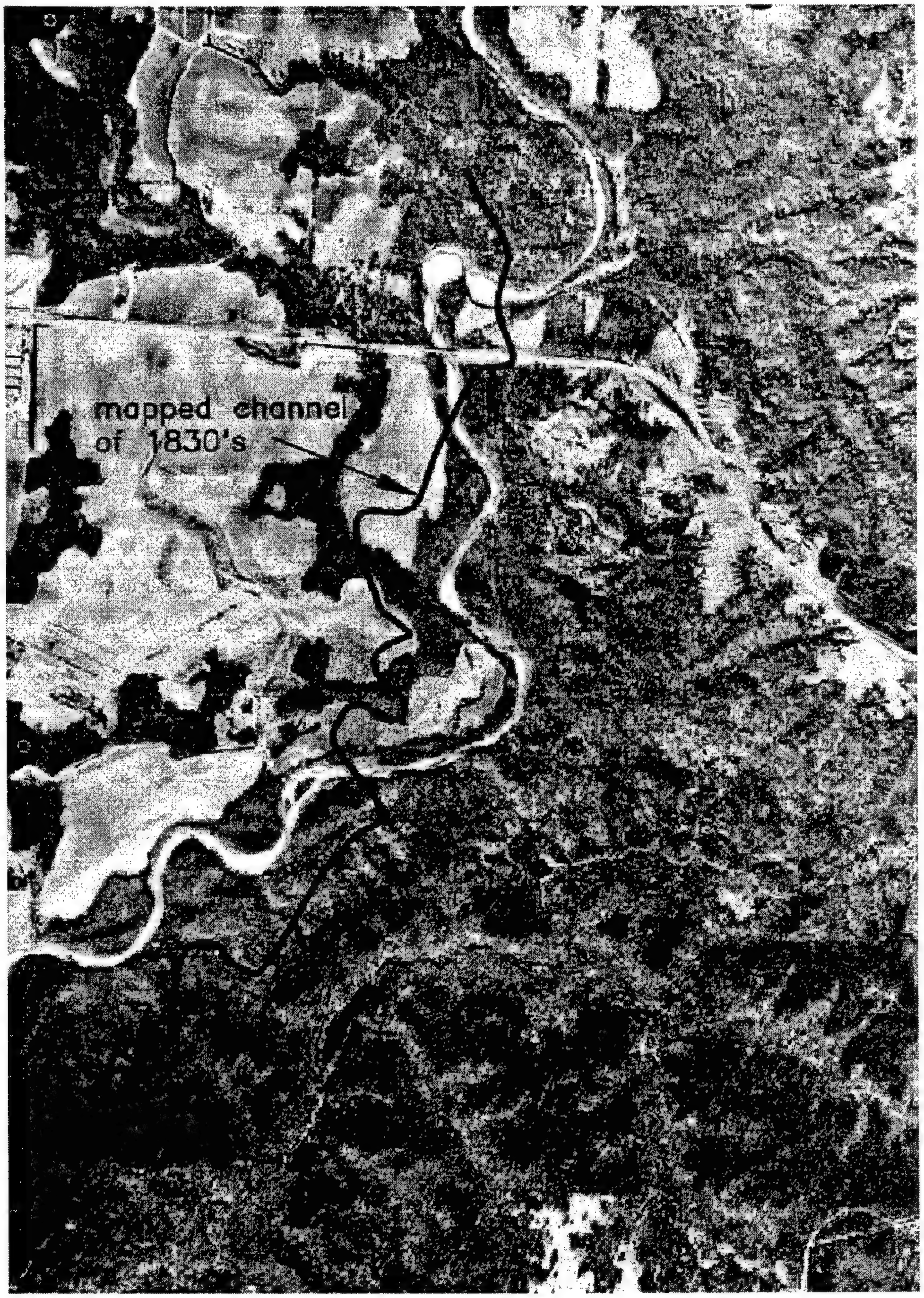


Figure 4-2. Comparison of modern (1986) and presettlement (1830) channel locations, Fannegusha Creek, Mississippi

Table 4-3
Checklist for Field Inspection

Upstream Basin and Channel Conditions

- Topography, soils, vegetation, land use, ongoing changes
- Erosion/deposition zones, sediment sources
- Drainage/irrigation systems, diversions
- Geomorphic controls and boundaries

Channel Planform and Banks

- Geological and structural controls
- Channel shifting and migration
- Bank soils, stratigraphy, failures, ice, seepage
- Vegetation, bank protection, floodplain conditions

Channel Profile and Bed

- Profile control points, irregularities
- Sediment deposits and stratigraphy
- Sizes and movement of bed material
- Degradation and aggradation

Water Surface Profile and Hydraulics

- High-water marks, debris/ice jams, flood conditions
- Velocities and roughness

Downstream Reaches

- Prior interference
- Features susceptible to upstream changes

General

- Photographs
- Overflight
- Witnesses to past floods
- Past interferences and responses

Note: Also see Appendix E of EM 1110-2-4000.

(Some items may be more easily obtainable from reports, maps, and aerial photos.)

(2) Active zones of erosion and deposition and evident sediment sources: sheet, rill, and gully erosion, etc. (Figure 4-3).

(3) Drainage and irrigation systems and diverted inflows and outflows.

(4) Tributary instability: gullying, headcutting, etc. (Figure 4-4).

(5) Dominant geomorphic controls: ridges, scarps, landform and channel type boundaries, etc. (see paragraphs 2-1 and 2-2). (May require specialist input.)

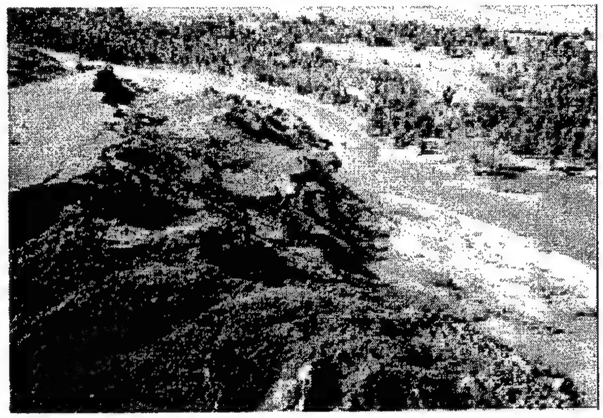


Figure 4-3. Major sediment source: valley landslide

Figure 4-4. Tributary gully

b. Channel planform and banks.

(1) Geological and structural controls on stream migration: valley walls, outcrops of rock and clay, clay plugs, bridges and dams, etc.

(2) Channel shifting and migration processes: meandering, cutoffs, braiding, etc.

(3) Bank soils and stratigraphy (Figure 4-5): composition, grain size ranges, layering, lensing, etc.

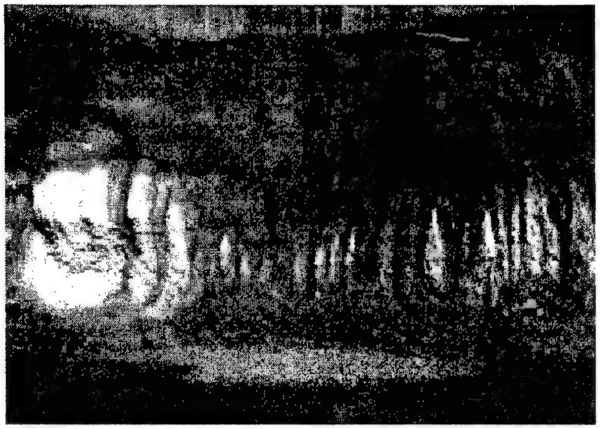


Figure 4-5. Stratification of bank soils

(4) Bank failures and erosion (Figure 4-6): locations, causes, and mechanisms (see paragraph 2-8).

Figure 4-6. Bank failure

(5) Drainage and seepage conditions especially after high flows (Figure 4-7), adjacent impoundments, irrigation, and cultivation practices.

(6) Types and densities of vegetation and root systems on banks and floodplain, and their significance with respect to erosion, slope stability, hydraulic roughness, trapping of sediment and debris, channel shifting, etc. Age and succession of vegetation on channel banks and bars can sometimes indicate rates of shifting and heights of flooding.

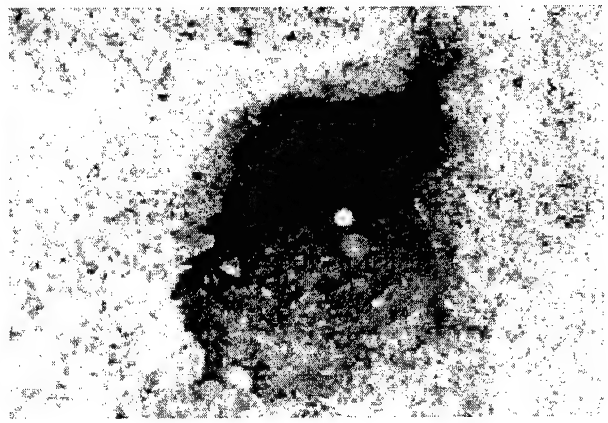


Figure 4-7. Piping and seepage in bank

(7) In cold regions: ice action on banks and vegetation, freeze-thaw action, frozen ground and ice lenses (see Figures 2-27 and 2-28; geotechnical input may be required).

(8) Existing and past bank protection work, damage, and failures and their causes.

(9) Floodplain conditions: natural and artificial levees, obstructions to flow, presence and clearing of vegetation, hydraulic roughness, local drainage inflow points, etc.

c. Channel profile and bed.

(1) Profile controls: outcrops, falls and rapids, nick points and zones (Figure 4-8), culverts, weirs, beaver dams, etc.

(2) Irregularity of streambed, occurrence of scour holes and shoals, alluvial bed forms, etc.

(3) Locations, forms, and grain size distributions of sediment deposits and bars (Figure 4-9).

(4) Thicknesses of active bed sediment, where probing or excavation to substratum is practicable.

(5) Indications of frequency of bed sediment movement; largest bed sediment sizes moved in past floods; relative intensity of bed sediment transport in the context of streams generally or of the region in question.

Figure 4-8. Nick zone in degrading channel (clay layer)

Figure 4-9. Channel bar with various sediment classes and debris

(6) Evidence of degradation: perched tributaries (Figure 4-10), exposed bridge piling (Figure 4-11), banks undercut both sides, etc.

(7) Evidence of aggradation; reduced bridge clearances, overtopped levees, buried intakes, etc.

d. Water surface profile and hydraulics.

(1) Recent high-water marks and probable dates.

(2) Water marks of afflux and drawdown around bridge piers (Figure 4-12). (Can sometimes be used to infer flood velocities.)

(3) Debris jams and accumulations.

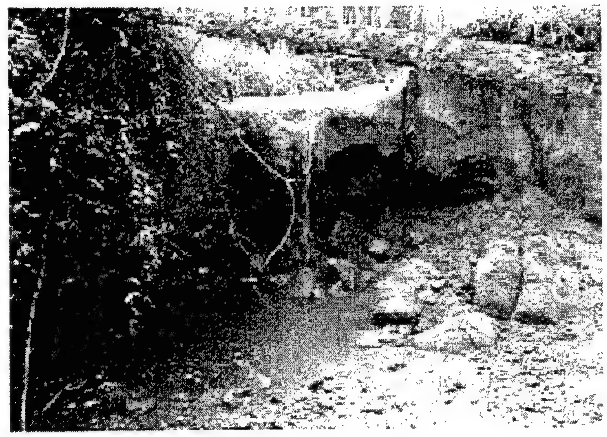


Figure 4-10. Mouth of perched tributary

Figure 4-11. Exposed bridge piling

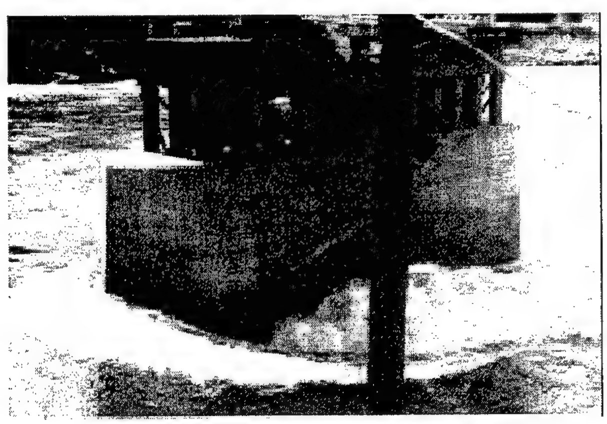


Figure 4-12. Flood stain marks on piers

(4) Evidence of ice jams and accumulations: tree scars, stripped vegetation, etc.

(5) Local photographs or witnesses' descriptions of flood conditions: depths of overbank flooding, standing waves, directions of attack on banks, overflow and escape routes, etc.

(6) Approximate velocities as observed.

(7) Estimates of hydraulic roughness based on general experience of channels (for confirmation purposes when other means of estimating are available).

e. Upstream and downstream reaches. Channel conditions should be inspected for some distance upstream and downstream of the project reach, with particular attention to features likely to impact on the project or susceptible to project-induced changes. Points to consider include how all the flood flows will be guided into the project channel at the upstream end; existing and potential upstream debris production; and downstream degradation as evidenced by headcuts (see paragraphs 3-18 through 3-23). Upstream and downstream reaches may require further attention at a later project stage.

4-6. Channel and Floodplain Surveys

a. Topography.

(1) Topographic or photogrammetric surveys to provide ground contours, channel and floodplain cross sections, and longitudinal profiles are normally required for the basic flood control aspects of the project. Attention to a number of points can improve the usefulness of survey information for stability evaluation.

(2) Cross sections should show margins and significant changes of vegetation cover, elevations of visible changes in bank soils, bank protection, water levels at time of survey, and detectable high-water marks. Section locations should be selected to cover a representative range of planform types - bends, straights, points of inflection, etc. - and a range of channel widths. If recent aerial photographs or a photomosaic plan is available, they can be used to select cross-section locations in advance and then to identify the locations on the ground. An example cross section is shown in Figure 4-13.

(3) The longitudinal profile should show bed levels, low or ordinary water levels, top of banks, and high-water

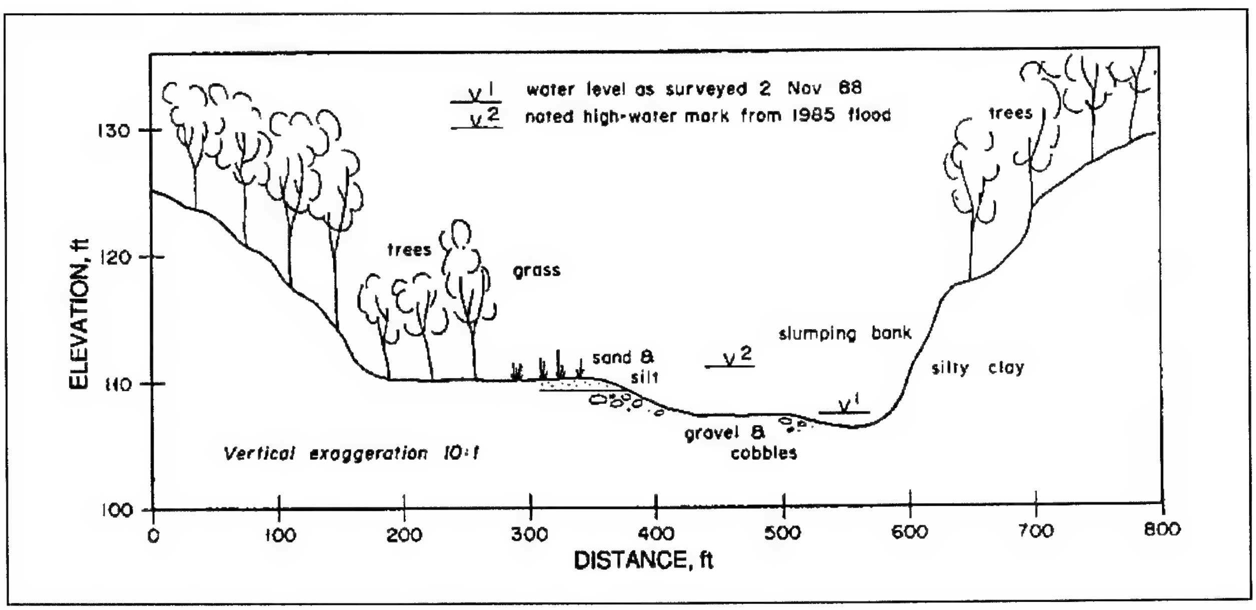


Figure 4-13. Example survey cross section

levels. Various bases for these delineations can be used. The bed levels may be along center line or along the thalweg (locus of deepest points). The low or ordinary water level may be a surveyed line on a specific date or a computed line corresponding to mean annual flow or other hydrologic parameter. The high-water level may be a surveyed high-water mark or a computed line corresponding to a flood of specified return period. For streams with definite floodplains, tops of bank lines should correspond more or less to floodplain levels unless there are bank levees. Notable discontinuities in the bed such as nick points, rapids and falls, and structures should be shown. An example profile is shown in Figure 4-14.

(4) Distances shown in profiles of single-channel streams should normally be measured along the channel center line. Where the stream splits into two or more channels, the main or largest channel should be used. In fully braided systems it is more practical to measure along the center of the braided belt. The basis for distance measurement should be clearly stated. Fixed points such as road crossings and tributary confluences should be shown. Quoted slopes should be based on fall divided by distance. When a stream has been shortened by previous channelization work and superimposed profiles are to be shown, it is best to superimpose fixed points such as bridges and show different distance scales; otherwise, false impressions of degradation and aggradation may be conveyed. Furthermore, exercise care when evaluating cross-section and profile data taken over time, i.e., low water, rising hydrograph, falling hydrograph, etc., when assessing aggradation and degradation trends.

b. Soils and materials.

(1) Samples of bed and bank materials should be taken for analysis of grain size distributions and for determination of other properties as required. The locations and frequency of sampling should be selected on the basis of previous field inspection and aerial photo interpretation.

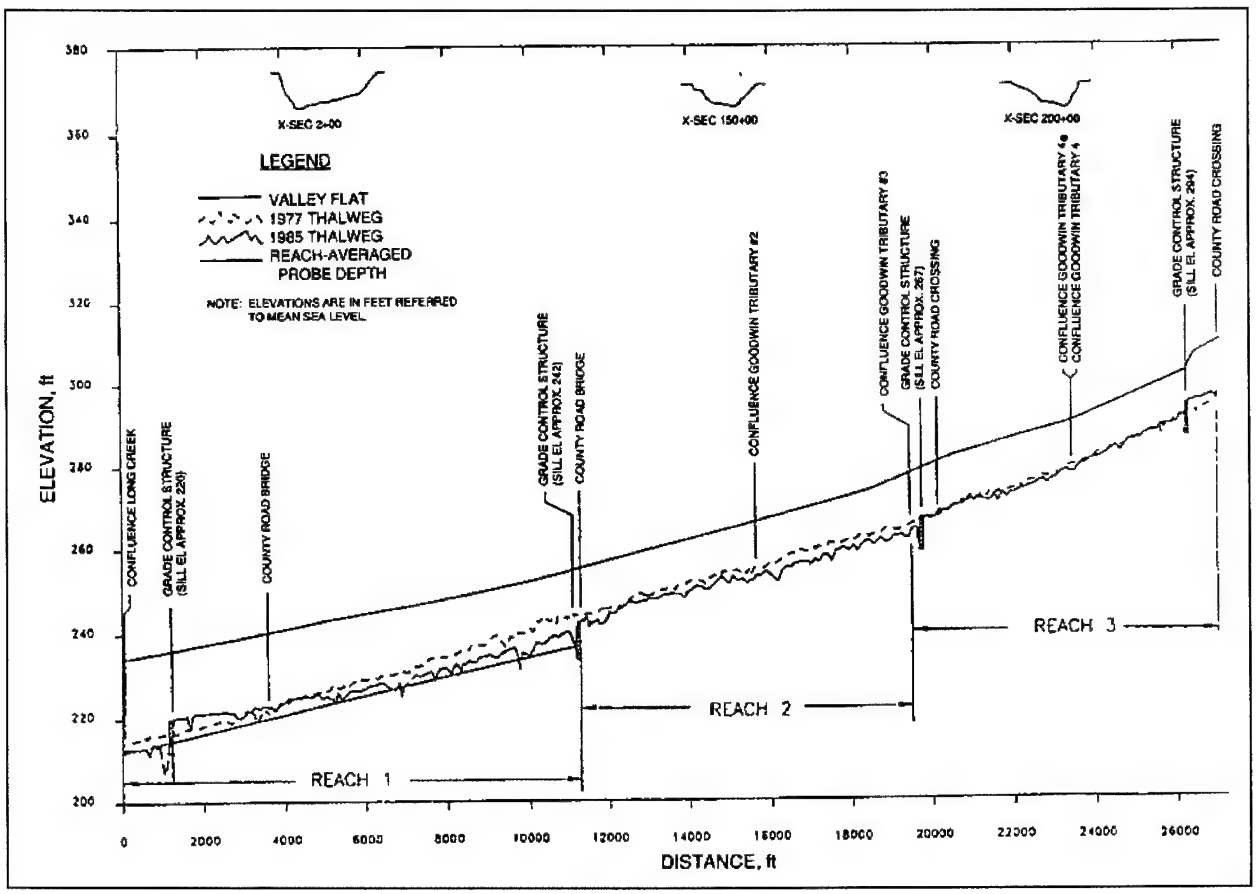
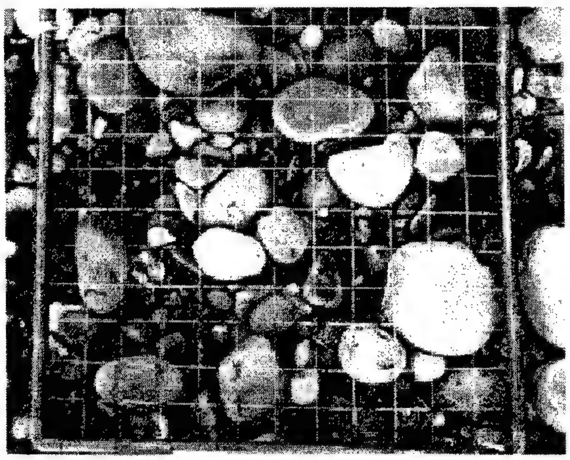


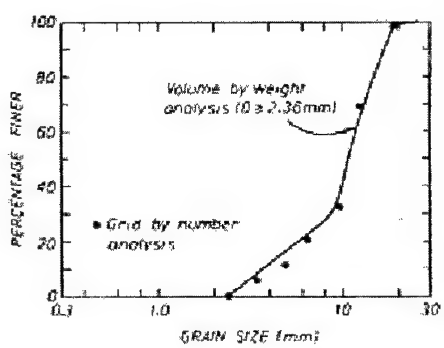
Figure 4-14. Example of stream profile

Due account should be taken of variation of soils and sediments along and across the stream, below the streambed, and up the banks.

(2) With coarse bed materials, collection of samples large enough for meaningful grain size analysis may be inconvenient. An alternative is to photograph the surface of channel bars though a wire grid, and to analyze the surface distribution from the photographs (Figure 4-15). If the surface material is similar to the underlying material, a surface distribution by number is more or less equivalent to a bulk distribution by weight (see Kellerhals and Bray 1971; Hey and Thorne 1983; Diplas and Sutherland 1988). In some coarse-bed streams, however, surface and underlying distributions of bed material are considerably different because of armoring effects. Armoring is more likely in streams where the bed is relatively inactive than in streams with frequent bed transport. If armoring is present, it is preferable to collect bulk samples that include subsurface material as well as the larger sizes in the armor layer.



a. Typical grid photograph



b. Comparison of grid by number analysis with volume by weight analysis-laboratory tests (Diplas and Sutherland 1988; courtesy of American Society of Civil Engineers)

Figure 4-15. Grid photograph of coarse sediment and comparison of analysis methods

(3) In streams with relatively fine or loose bed material of limited thickness overlying more consolidated materials, the bed can be probed at intervals with a metal rod to determine thicknesses of active sediment. Such determinations are particularly valuable in considering potential for bed degradation. Geophysical methods of determining sediment thickness are feasible in some cases. With very loose estuarial and coastal sediments, some form of echo sounding may be feasible. Where probing or indirect methods of investigating stratigraphy are not feasible, soil borings or excavations may be advisable.

c. Bank failure and erosion. The general characteristics of bank failure and erosion will be noted in the field inspection (see paragraph 4-4). In some cases a detailed survey of erosional sites may be required to relate erosional severity to bank soils, heights and slopes, etc. Related technical background is outlined in Section 5-3.

4-7. Streamflow and Related Data

a. General. Streamflow data are basic to engineering analysis of channel stability (see Section 5-3). Normally these data are analyzed for flood control aspects of the project. Data presentations required include discharge records, flood-frequency relationship, flow-duration relationship, and stage-discharge relationship. Where there is a hydrometric gauge in the basin, the first three can usually be generated for the project length without great difficulty. A gauge stage-discharge relationship, however, may be difficult to transfer to the project reach. In ungauged basins, synthetic discharge estimates may be generated from hydrologic analogy or from watershed modelling. In small flood control projects, lack of streamflow data often limits the practicability of stability analysis. If reliable streamflow information is not available, experienced judgment may be more useful than analysis.

b. Discharge records.

(1) The historical sequence of annual maxima is useful for interpreting field inspection and surveys. Especially in small basins, attention should be paid to peak instantaneous discharges rather than maximum daily discharges. If there has not been a large flood for many

years, the channel may convey a false impression of longterm stability. On the other hand, a recent extreme flood might have severely destabilized the channel, presenting an exaggerated impression of long-term instability.

(2) If the flood sequence exhibits peculiar features or anomalies, it is advisable to examine the gage history to assess possible changes due to subsidence or uplift or to shifts in gage location or datum.

c. Flood-frequency relationship. A graphical relationship using any standard method of plotting is usually sufficient. Extrapolation to return periods far beyond the length of the record should be regarded skeptically. Efforts should be made to determine the frequency of the bank-full discharge. If the stream has a definable bank-full condition and its return period appears to fall outside the range of 1 to 5 years, there may be a case for reviewing the hydrologic data, especially if they are synthesized.

d. Flow-duration relationship. A flow-duration relationship may be useful for a rough assessment of how frequently the streambed material is in motion, if used in conjunction with a beginning-of-motion analysis (see Section 5-3). It is also needed for estimating annual volumes of sediment transport. In small streams, it is particularly important to define the portion of the flow-duration curve with exceedances of 1 percent or less.

e. Stage-discharge relationship.

(1) A reliable stage-discharge relationship is needed for quantitative stability analysis. An incorrect stage-discharge relation may be quite misleading, especially if velocities are used as a stability criterion.

(2) Specific gage records, which plot stages versus time (usually in years) for fixed values of discharges, can be developed from the historical record of stage-discharge data for a particular gage. These are often valuable tools in assessing the vertical stability of the channel (see Figure 3-17).

(3) Where there is no suitable gage record, stage-discharge relationships are normally synthesized either by nonuniform flow analysis using HEC-2 or similar programs, or by uniform flow analysis of cross-section and slope data. The limitations of fixed-bed flow analysis as applied to mobile-boundary channels are not always sufficiently appreciated. Sections based on low-water surveys may be incorrect for high-water stages, because of channel scour and fill. If the channel is relatively uniform in cross section and slope, uniform flow analysis in which the Manning or similar equation is applied to an average cross section and slope may be sufficient and in some cases as reliable as nonuniform analysis.

(4) The greatest difficulty in synthesizing a stage-discharge relationship is correct estimation of hydraulic roughness, especially during the large floods that are critical for stability. Every effort should be made to check computed stages against observed or indicated water levels in past floods of known or estimated discharge.

4-8. Geologic and Geotechnical Information

a. Geologic and geotechnical information is important in evaluating channel stability. It is valuable to understand the geologic origins and geotechnical properties of soils and sediments that interact with the channel processes. Information may be obtained from previous reports or involvement of a specialist.

b. In a dynamic channel system, rock outcrops, cemented gravels, tills, and clay plugs may form hard points that resist erosion and constitute more or less fixed nodes in the plan form. Some cohesive or cemented deposits and soft rocks, however, break down fairly rapidly into cohesionless sediments under the influence of weathering, particularly freeze-thaw and wet-dry cycles.

c. Geotechnical conditions that often result in bank failure in alluvial and glacial outwash soils include internal erosion of dispersive clay, silt, and fine sand through piping; tension crack formation and displacements; saturation and drawdown with flood rise and recession; and surface slaking and soil flows due to temperature and moisture changes.

d. Lacustrine and glaciolacustrine soils and low-flow deposits may be layered or "varved." Many banks in such soils exhibit slope instability.

e. Wind-deposited soils such as loess, composed of silt and clay-size particles, can stand on very steep slopes when dry, but are susceptible to loss of cementation when wetted and to erosion by overland flows.

f. Colluvial soils, derived from weathering of underlying rocks and subsequent gravity movement, are often found on steep river valley slopes. In wet periods they are subject to reduction in strengths and increases in unit weight, which tend to initiate bank failures. They may contain silty clay and weathered rock fragments.

Erosion of the silty clay may leave a temporary layer of rock fragments, too thin to act as a stabilizing berm, that becomes covered by subsequent landslides.

g. Glacial till is generally a compact mixture of clay, silt, sand, gravel, and boulder sizes. Most deposits are fairly resistant to erosion, and most streams in a till environment exhibit relatively low rates of erosion and channel shifting. Long-term incision of streams in till soils often leaves a surficial armor layer of cobbles or boulders that is resistant to movement by the stream.

4-9. Sediment Transport

Data needs for analysis of sediment transport are covered in EM 1110-2-4000, to which reference should be made if a full sedimentation analysis is judged advisable. In many small to medium flood control projects the necessary time and resources are not available; yet some qualitative assessment is desirable. The following points may assist such an assessment:

a. The relative degree of bed material transport - for example, low, medium, or high - can be judged to some extent by experienced observers from the aerial and ground features of the channel under relatively low flow conditions. Channels with high transport have large areas of exposed bars exhibiting clean rounded bed material without growths and vegetation. Channels with low transport tend to have few exposed bars, stable banks, and individual grains or stones covered with algae.

b. The degree of wash load can be similarly judged from recent silt and clay deposits in slack-water areas and on the upper banks and floodplain. Channels with high wash load will exhibit substantial thicknesses of silt/clay not yet colonized by vegetation. Channels with low wash load will have clean granular sediments on the upper banks and floodplain.

c. Notwithstanding *a* and *b* above, appearances are sometimes deceptive in the absence of local or regional experience. For example, the appearance of a medium-transport channel may vary considerably from arid to humid regions and from cold to hot regions. Description of bed material transport as low, medium, or high refers essentially to high-flow conditions, for example, discharges like the mean annual flood. Such a scheme may not be useful for ephemeral streams in arid regions, where floods capable of transport may occur at rare intervals and the channel is dry much of the time.

d. In meandering streams exhibiting systematic migration through an alluvial floodplain, the degree of bed-sediment transport is linked to the rate of meander shifting. The severity of bank recession can be visualized in terms of channel widths; for example, a rate of one channel width per year would be very high, whereas a rate of 1 percent of channel width per year would be quite low.

e. A braided planform usually but not always indicates high bed material transport. A contorted meander planform without visible point bars usually indicates low bed material transport, although wash load may be high. More generalized relationships of this type are discussed in paragraph 2-3.

Chapter 5
Evaluation of Stability

5-1. General

a. The purpose of this chapter is to provide assistance in evaluating the stability of existing or proposed channels that form part of a flood control project. The meaning of stability as used herein is defined in paragraph 1-1.

b. A stability evaluation of some type should be conducted early in project planning to screen out alternatives that would present serious stability problems and to identify needs for further studies. As planning progresses, successive evaluations with increasing detail may be required. In some environments, potential future consequences of erosional instability can have an overwhelming impact on the long-term viability of a project. Once key planning decisions have been made, it may be difficult to modify the project sufficiently to avoid serious stability problems.

c. There has been a tendency in the past to defer treatment of stability problems to postconstruction maintenance, and such a policy has sometimes been supported by cost-benefit studies. It is often difficult, however, to implement adequate maintenance even where it is clearly provided for in project agreements. The expected time scale of channel response has an important bearing on the advisability of relying on maintenance. It may be reasonable to rely on maintenance to accommodate gradual development of instability but not rapid development.

d. Stability evaluation will normally be directed toward preparation of a statement describing the stability characteristics of the existing channel system and the stability implications of the proposed project. Recommendations will be formulated on whether special measures are required to counter existing problems or adverse impacts.

5-2. Levels of Detail

Evaluation can be done at various levels, ranging from a purely qualitative process based on inspection to a partly quantitative process using numerical data and analyses. When stability evaluation indicates a need for detailed studies of sediment yield, transport, or deposition, reference should be made EM 1110-2-4000. The appropriate level of detail for a particular evaluation depends on the status of the study, the perceived seriousness of potential problems, the scale of the project, and the resources available.

5-3. Technical Approaches and Their Application

a. Approaches and techniques that have been used for quantitative evaluation of channel stability include allowable velocity, allowable shear stress, stream power, hydraulic geometry relationships, sediment transport analysis, and bank slope stability analysis. Most of those techniques do not provide a complete solution, and are best regarded as aids to judgment rather than self-sufficient tools. For example, available analytical techniques cannot determine reliably whether a given channel modification will be liable to meander development, which is sensitive to difficult-to-quantify factors like bank vegetation and cohesion. Locally or regionally developed approaches and data that have been found to give satisfactory results should normally be preferred over the more general approaches described herein.

b. The erosional and depositional stability of mobile-boundary channels is a complex multidimensional problem. Analytical knowledge is not as thorough as that for nonerodible channels. Previous experience with the behavior and response of similar channels in a similar environment is an invaluable guide to evaluation. If analysis conflicts with experience, the analysis should be reviewed critically. Caution should be observed against relying on a single method. The analytical tools applied should be appropriate to the anticipated forms of instability.

c. Adequate resistance to erosion does not necessarily result in freedom from instability or sedimentation if the channel has substantial inflows of bed material. The simpler methods such as allowable velocity or shear stress basically indicate what hydraulic conditions (velocity, depth, slope, etc.) will initiate erosion in the absence of significant sediment inflows (see Figure 2-20). Modified or more complex methods are required to take account of sediment inflows. In flood control channels, avoidance of sediment deposition may be as important as avoidance of erosion.

d. Simple formulas for computing values of specific parameters - for example, the Manning velocity formula - generally yield a cross-sectional average value. This average value may be greatly exceeded at critical points where erosion occurs, for example, on the outside bank of a bend. On the other hand, at points of sediment

deposition the local value may be much less than the cross-sectional average. Adjustment factors for cross-sectional distribution may be needed in such cases.

5-4. Allowable Velocity and Shear Stress

The concepts of allowable velocity and allowable shear stress are closely linked. They have been used mainly to design channels free from boundary erosion. In channels transporting sediment, however, design should ensure that sediment outflow equals sediment inflow. Modifications of allowable velocity or shear stress to allow for sediment transport have been proposed in a few references, but are of limited applicability. The information provided below is in summary form. More extensive information on allowable velocity and shear stress concepts is available in numerous textbooks and manuals on mobile boundary hydraulics and sediment transport.

a. Allowable velocity data.

(1) The concept of allowable velocities for various soils and materials dates from the early days of hydraulics. An example of simple velocity data is given by Table 5-1, which is provided as a guide to nonscouring flood control channels in EM 1110-2-1601. In the reference, the table is supplemented by graphical data for coarse gravel and boulder materials.

(2) Another example is Figure 5-1, which shows data provided by the Soil Conservation Service (U.S. Department of Agriculture (USDA) 1977). This discriminates between "sediment-free" and "sediment-laden" flow. Adjustment factors are suggested in this reference for depth of flow, channel curvature, and bank slope. In this context, "sediment laden" refers to a specified concentration of suspended sediment.

b. Allowable shear stress data.

(1) By the 1930's, boundary shear stress (sometimes called tractive force) was generally accepted as a more appropriate erosion criterion. The average boundary shear stress in uniform flow (Figure 5-2) is given by

$$\tau_0 = \gamma RS \tag{5-1}$$

where

γ = specific weight of water

R = hydraulic radius

S = hydraulic slope

Table 5-1
Example of Simple Allowable Velocity Data
(From EM 1110-2-1601)

Channel Material	Mean Channel Velocity, fps
Fine Sand	2.0
Coarse Sand	4.0
Fine Gravel	6.0
Earth	
Sandy Silt	2.0
Silt Clay	3.5
Clay	6.0
Grass-lined Earth (slopes less than 5%)	
Bermuda Grass	
Sandy Silt	6.0
Silt Clay	8.0
Kentucky Blue Grass	
Sandy Silt	5.0
Silt Clay	7.0
Poor Rock (usually sedimentary)	10.0
Soft Sandstone	8.0
Soft Shale	3.5
Good Rock (usually igneous or hard metamorphic)	20.0

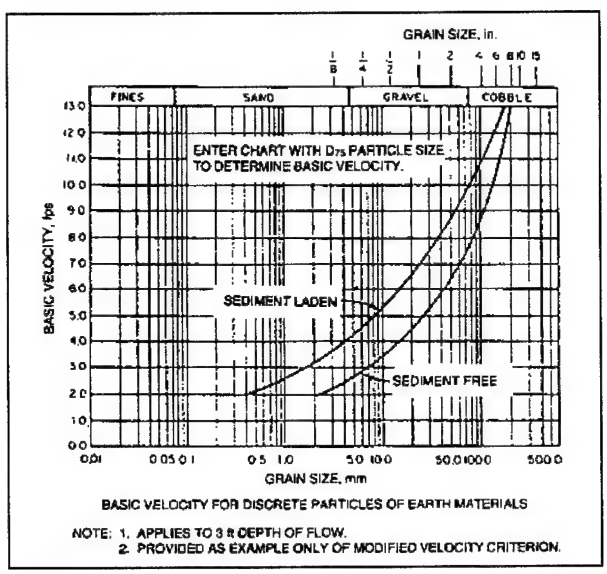


Figure 5-1. Example of allowable velocity data with provision for sediment transport (USDA 1977)

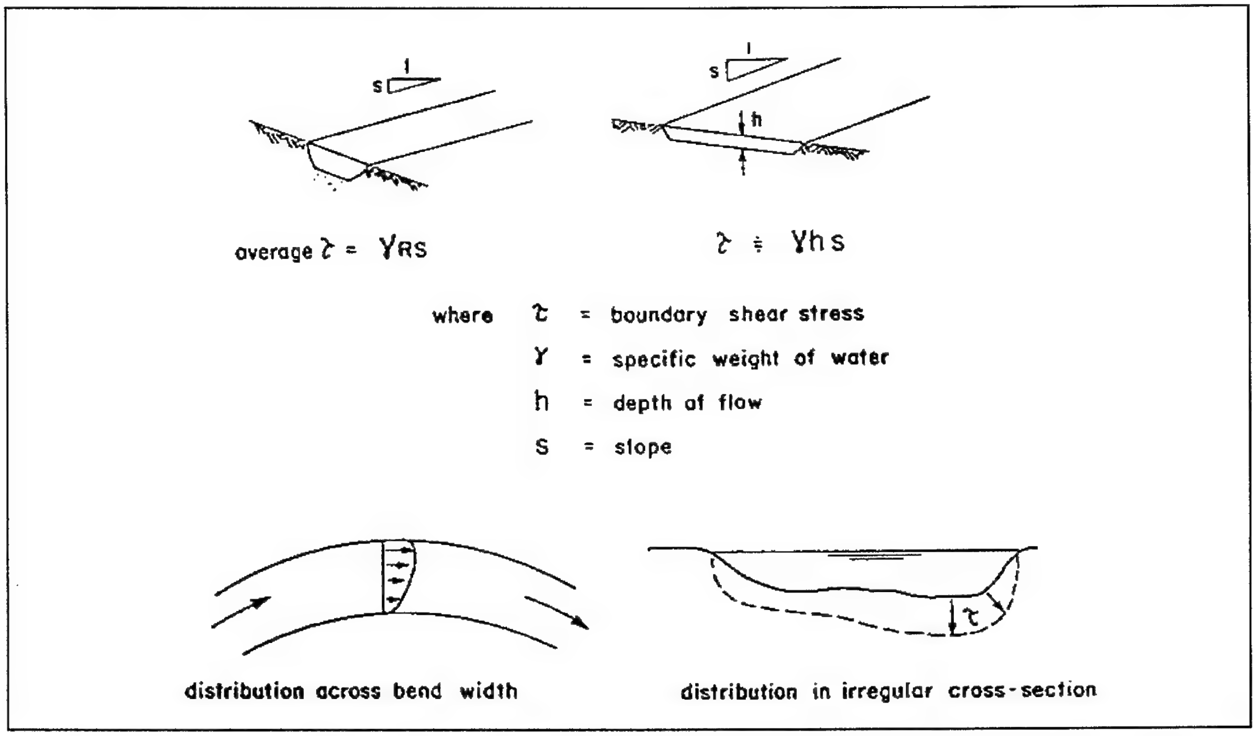


Figure 5-2. Boundary shear stress in uniform flow

Values for incipient erosion (or initiation of motion) of noncohesive materials are usually presented in nondimensional form.

(2) Figure 5-3 shows a modified version of the well-known Shields diagram for initial movement or scour of noncohesive uniformly graded sediments on a flat bed. The diagram is applicable theoretically to any sediment and fluid. It plots the Shields number (or mobility number), which combines shear stress with grain size and relative density, against a form of Reynolds number that uses grain size as the length variable. For wide channels with hydraulic radius approximately equal to depth, the relationship can be expressed as

$$\frac{\tau_0}{\gamma_s' D} = \left[\frac{dS}{(s-1)D}\right] = f\left(\frac{V_* D}{\nu}\right) \qquad (5\text{-}2)$$

where

γ_s' = submerged specific weight of sediment

D = grain size

d = depth of flow

s = dry relative density of sediment

$V*$ = shear velocity defined as $\sqrt{\tau_0/\rho}$

ρ = fluid density

ν = kinematic viscosity

(3) For sediments in the gravel size range and larger, the Shields number for beginning of bed movement is essentially independent of Reynolds number. For wide channels the relationship can then be expressed as

$$\frac{dS}{(s-1)D} = constant \qquad (5\text{-}3)$$

The constant is shown as 0.06 in Figure 5-3, but it is often taken as 0.045, or even as low as 0.03 if absolutely no movement is required. For widely graded bed materials, the median grain size by weight (D_{50}) is generally taken as the representative size, although some writers favor a smaller percentile such as D_{35}.

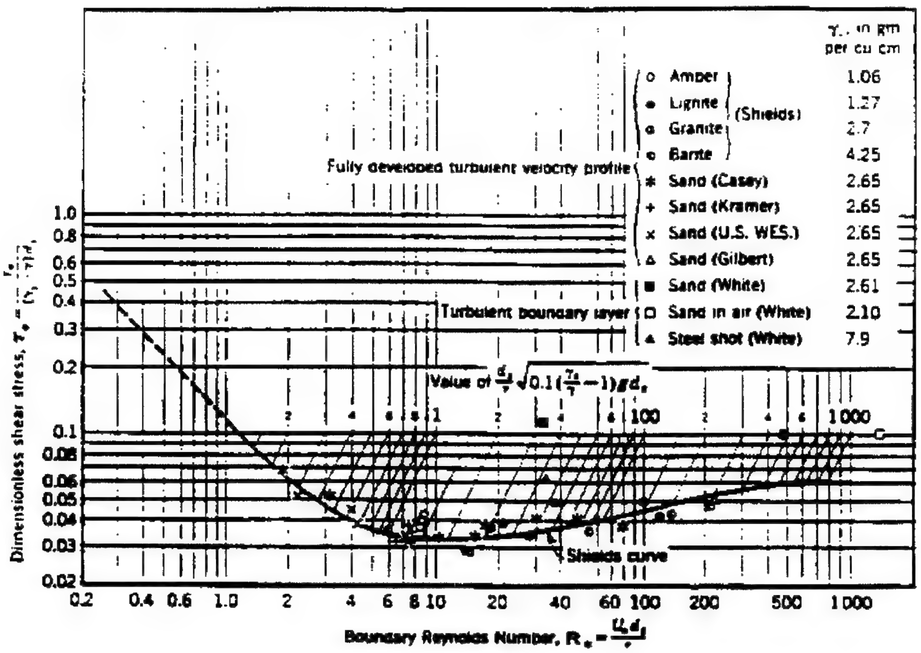


Figure 5-3. Shields diagram: dimensionless critical shear stress

(4) The allowable shear stress concept has also been applied to semicohesive and noncohesive soils, but values do not correlate well with standard geotechnical parameters because erosional resistance is affected by such factors as water chemistry, history of exposure to flows, and weathering (Raudkivi and Tan 1984). Analysis of experience with local channels and hydraulic testing of local materials are generally recommended. Figure 5-4 gives an example of allowable shear stresses for a range of cohesive materials, but where possible, values should be compared against the results of field observation or laboratory testing.

c. Allowable velocity-depth relationships. Theoretical objections to use of velocity as an erosion criterion can be overcome by using depth as a second independent variable. An example of a velocity-depth-grain size chart is shown in Figure 5-5. This particular chart is intended to correspond to a small degree of bed movement rather than no movement. Its derivation is explained in Appendix B. It should be taken as indicative of trends only and not as definitive guidance for the design of flood control channels.

d. Cautions regarding allowable velocity or shear stress. The following limitations of the allowable velocity

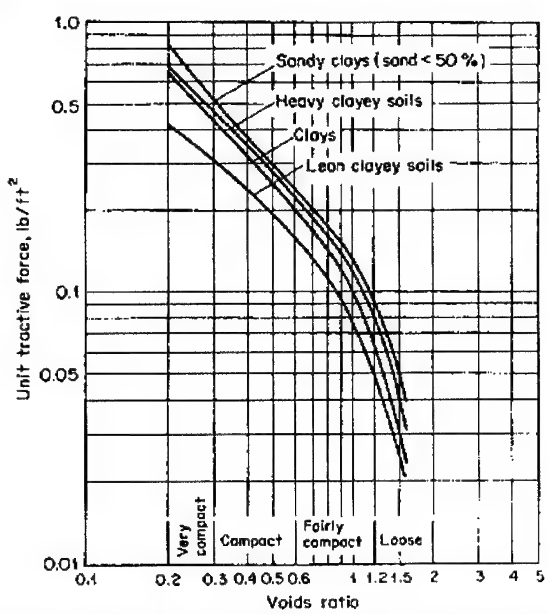


Figure 5-4. Example of allowable shear stresses ("tractive forces") for cohesive materials (Chow 1959; courtesy of McGraw-Hill)

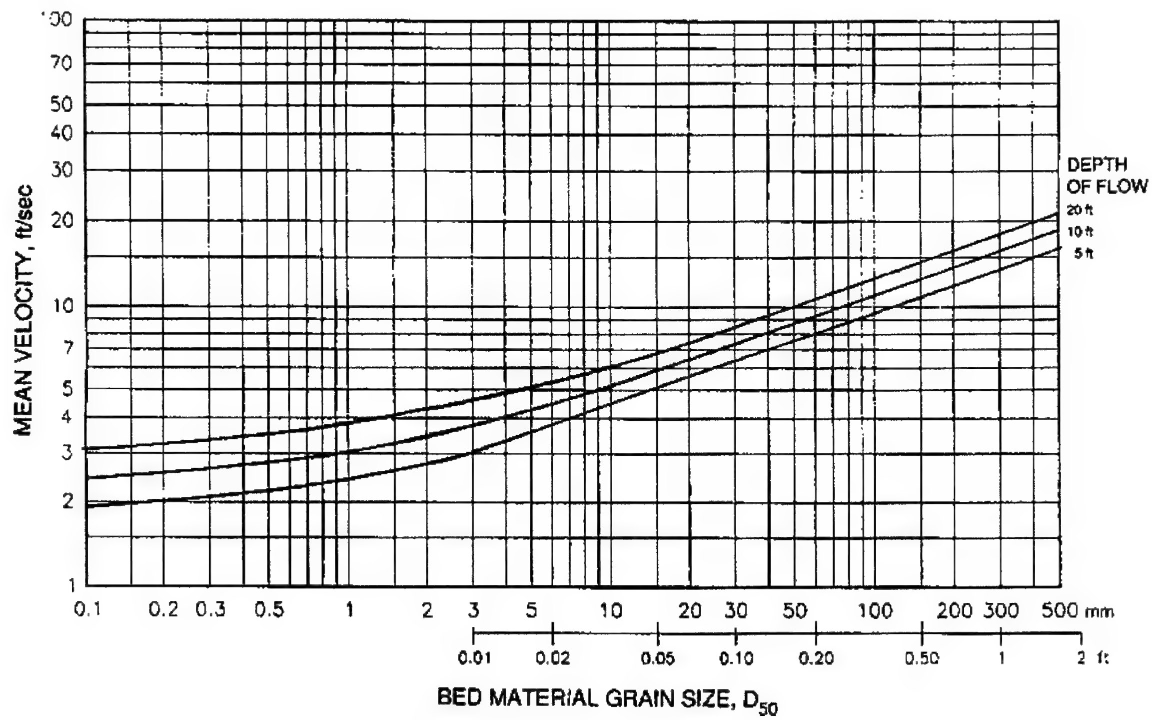


Figure 5-5. Example of allowable velocity-depth data for granular materials. For derivation see Appendix B

and allowable shear stress approaches should be recognized:

(1) For channels with substantial inflows of bed material, a minimum velocity or shear stress to avoid sediment deposition may be as important as a maximum to avoid erosion. Such a value cannot be determined using allowable data for minimal erosion.

(2) In bends and meandering channels, bank erosion and migration may occur even if average velocities and boundary shear stresses are well below allowable values. (Conversely, deposition may occur in local slack-water zones even if average values are well above maximum deposition.) Information on cross-sectional distributions of velocity and shear stress in bends is provided in EM 1110-2-1601.

(3) An allowable velocity or shear stress will not in itself define a complete channel design, because it can be satisfied by a wide range of width, depth, and slope combinations (Figure 5-6). It therefore has to be supplemented by additional guidelines for slope, width, or cross-sectional shape. In many cases of channel modification, the slope will be predetermined within narrow limits, and practicable limits of width/depth ratio will be indicated by the existing channel.

(4) The Shields relationship (Equation 5-2 and Figure 5-3) applies basically to uniform flow over a flat bed. In sand bed channels especially, the bed is normally covered with bed forms such as ripples or dunes, and shear stresses required for significant erosion may be much greater than indicated by the Shields diagram. Bed forms and irregularities occur also in many channels with coarser beds. More complex approaches have been used that involve separating the total shear stress into two parts associated with the roughness of the sediment grains and of the bed forms, of which only the first part contributes to erosion. In general, however, the Shields approach is not very useful for the design of channels in fine-grained materials.

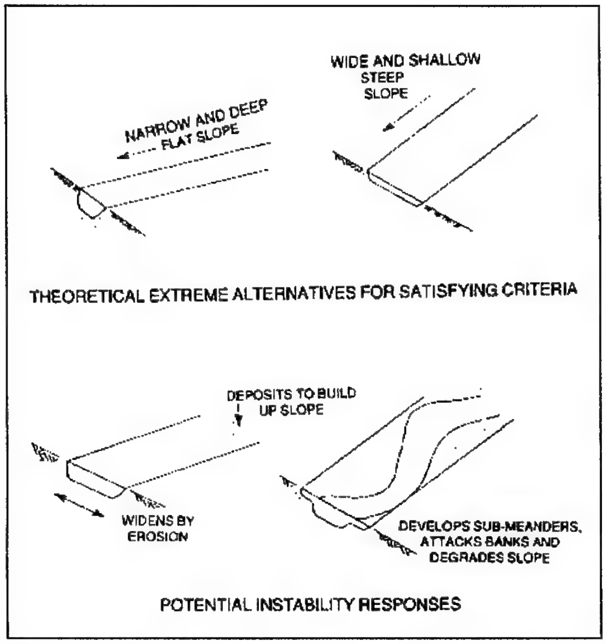


Figure 5-6. Insufficiency of allowable velocity or shear stress criterion for stability of alluvial channel

(5) Empirical data for allowable shear stress versus grain size in canals are widely published (Appendix C).

e. Guidelines for application. The following guidelines are suggested for computations and procedures using allowable velocity and shear stress concepts:

(1) Determine cross-section average velocities and/or shear stresses over an appropriate range of discharges. Under overbank flow conditions, determine in-channel values, not averages over a compound section (Figure 5-7). For existing channels, where possible use stage-discharge relations established from gaging stations or known watermarks; otherwise use hydraulic computations with estimated roughnesses. Stage-discharge relations in compound channels are reviewed by Williams and Julien (1989).

(2) A practical design approach for modification of existing channels is to match the velocity-discharge curve of the existing channel so far as possible by controlling cross section, slope, and roughness. Experience with response to local constrictions and widenings in alluvial channels generally supports this approach; these tend to scour or fill to restore more or less the natural velocity.

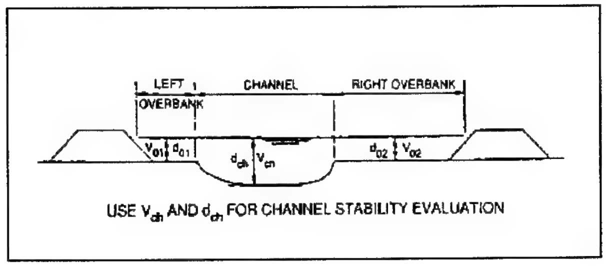


Figure 5-7. Velocities and depths in compound cross section

(3) In active alluvial streams, roughness may change appreciably between low and high stages (Figure 5-8). Bed roughness predictors (EM 1110-2-1601) can be used as a guide. For erosion checks it is conservative to estimate roughness on the low side, whereas for levee design it is conservative to estimate on the high side.

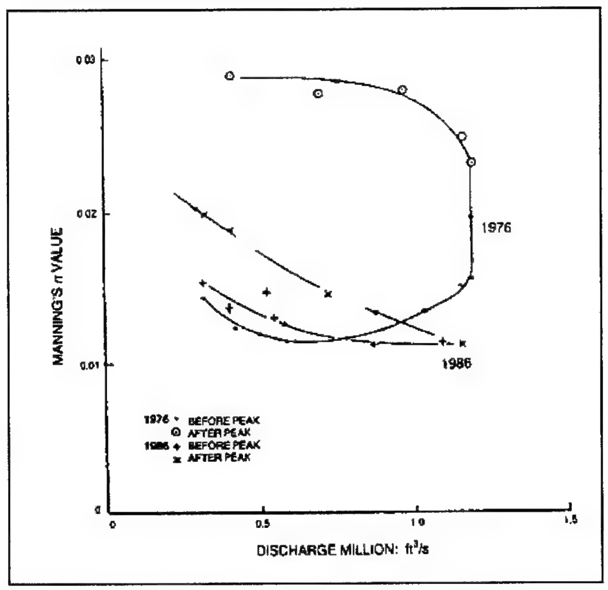


Figure 5-8. Roughness changes in a large sand bed river during floods (Ackers 1988; courtesy of Institution of Civil Engineers)

(4) If cross sections and slope are reasonably uniform, computations can be based on an average section. Otherwise, divide the project length into reaches and consider values for small, medium, and large sections.

(5) Determine the discharge for incipient erosion from the stage-velocity or discharge-velocity curve, and determine its frequency from a flood-frequency or flow-duration curve. This may give some indication of the potential for instability. For example, if bed movement has a return period measured in years, which is the case with some cobble or boulder channels, the potential for extensive profile instability is likely to be negligible. On the other hand, if the bed is evidently active at relatively frequent flows, response to channel modifications may be rapid and extensive.

5-5. Empirical Relationships for Channel Properties

a. Concepts of channel equilibrium (or regime) and hydraulic geometry are explained in Section II, Chapter 2. Empirical relationships expressing the width, depth, and slope (or velocity) of alluvial channels as separate functions of a dominant or channel-forming discharge were developed by (among others) Lacey (1929-30), Blench (1957), and Simons and Albertson (1963). References covering more recent developments, applications, and criticisms include Hey and Thorne (1986), Stevens and Nordin (1987), and White (1988). Relationships of this type may be useful for preliminary or trial selection of channel properties.

b. In considering flood control channels for a specific location, it is best to use locally or regionally developed relationships for hydraulic geometry, for example, Figure 2-21. If this is not possible, Figures 5-9, 5-10 and 5-11 show tentative relationships that may be useful as rough guides for selecting values of width, depth and slope, respectively, as functions of channel-forming discharge and bed material. Background on the development of those charts is provided in Appendix B. The following guidelines and limitations should be observed:

(1) Where possible, reach-averaged data for existing channels should be plotted and compared with the indications of the charts, using bank-full discharge as channel-forming. If bank-full discharge is not determinable, an alternative discharge parameter can be used (paragraph 2-8*a*). This comparison can indicate how compatible the stream system is with the assumptions of the charts. The trends of the charts can then be used to estimate changes appropriate for the modified project channel, particularly for modifications that involve increased in-channel flows, for example, as a result of close-set levees or floodwalls.

(2) The charts are likely to be most compatible with single-channel sand or gravel systems with relatively low bed material transport. A multichannel system, which usually indicates higher bed material transport, will tend to have greater overall widths and slopes but smaller depths, although individual branches may fit the curves reasonably in relation to their partial bank-full discharges.

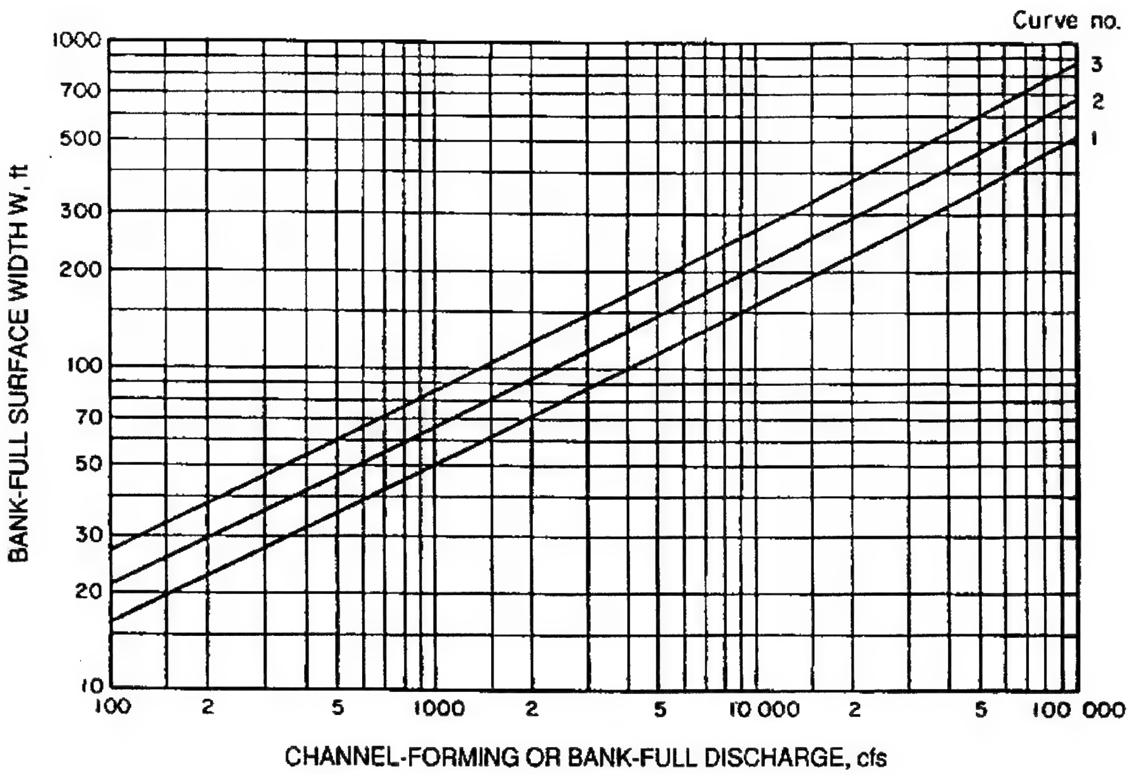
(3) If bed material transport is high, the slopes indicated in Figure 5-11 may be much too low and the depths in Figure 5-10 may be too high. This is especially true of channels with sand beds and of ephemeral channels where much of the flow occurs as flash floods with very high sediment transport. In perennial-flow gravel rivers with single channels, slopes are unlikely to be more than three times greater than those indicated by Figure 5-11. Width is fairly insensitive to bed material transport unless the stream is multichanneled or braided. If bed material transport is high, it is preferable to use a sediment budget analysis of the type referred to in paragraph 5-7*b*.

(4) Actively aggrading and degrading channels can go through a complex cycle of response. In some stages of the response, they may exhibit large departures from normal hydraulic geometry relationships. For example, a channel in the earlier stages of active degradation (incision) may be abnormally narrow.

(5) The use of all three charts does not permit explicit selection of roughness and allowable velocity or shear stress. An alternative hybrid approach involves determining channel properties using three relationships: the width-discharge relationship of Figure 5-9; the Manning formula with a roughness estimate based on guidelines or experience; and an allowable velocity or shear stress.

5-6. Analytical Relationships for Channel Properties

a. Several investigators have proposed that stable channel dimensions can be calculated analytically by simultaneous solution of the governing equations. These methods consider discharge, sediment transport, and bed material composition as independent variables and width, depth, and slope as dependant variables. Three equations are required to solve for the three unknown variables. Equations for sediment transport and hydraulic resistance can be chosen, from among several that are available, for two of the required equations. Chang (1980) proposed that minimum stream power could be used as the third



TENTATIVE GUIDANCE: CURVE 1: STIFF COHESIVE OR VERY COARSE GRANULAR BANKS.
CURVE 2: AVERAGE COHESIVE OR COARSE GRANULAR BANKS.
CURVE 3: SANDY ALLUVIAL BANKS.

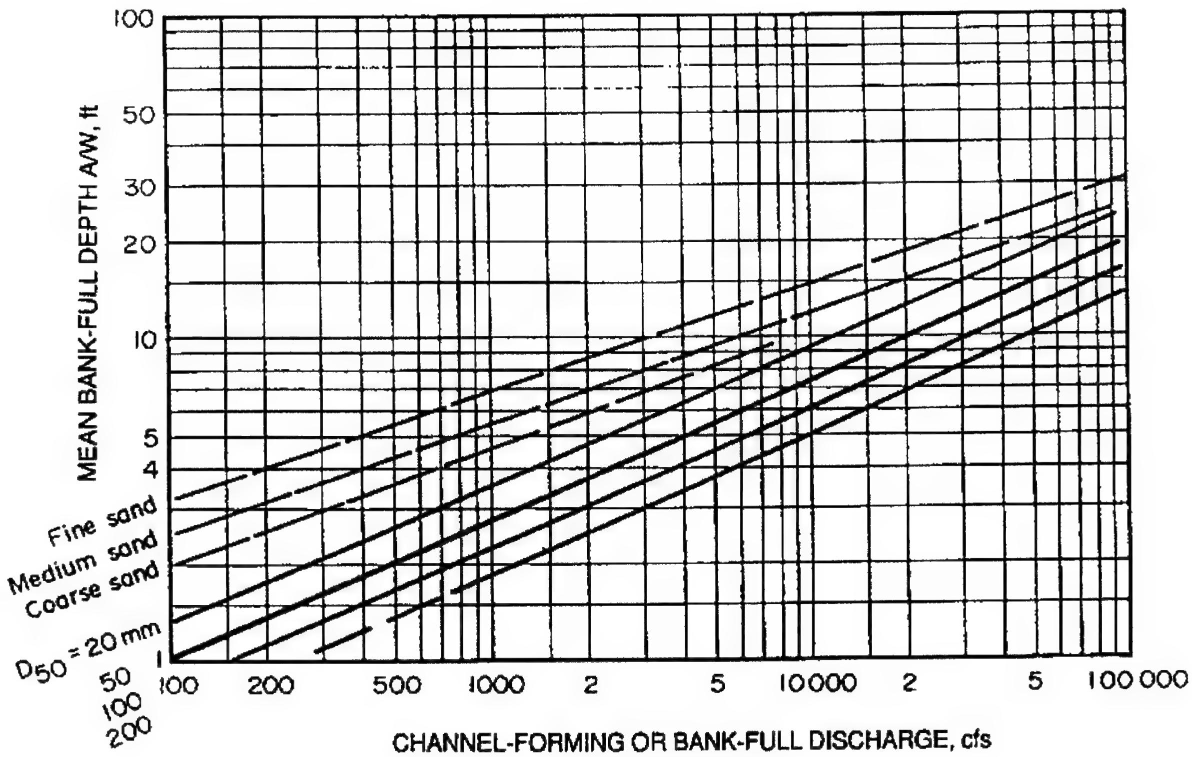
SEE PARAGRAPH 5-5 FOR LIMITATIONS.

FORMULA: $W = C Q^{0.5}$ WITH $C = 1.6, 2.1, 2.7$

Figure 5-9. Tentative guide to width-discharge relationships for erodible channels. See Appendix B for derivation.

equation. He combined the Engelund-Hansen sediment transport and flow resistance equations with the minimum stream power equation to develop a stable channel design method. Chang's method was verified using canal and flume data with large width-to-depth ratios and low bed material transport. White, Bettess, and Paris (1982) proposed that maximum sediment transport, which they demonstrated to be equivalent to minimum stream power, could be used as a third equation. They used their own flow resistance equation and the Ackers-White sediment transport equations in their stable channel design method. Their method was also tested using sand-bed canal and flume data with low bed material transport and large width-to-depth ratios. The method did not produce acceptable results in gravel-bed streams. The White, Bettess, and Paris method is available in the U.S. Army Corps of Engineers CORPS computer program package. Sample results are shown in Appendix C. The minimum stream power concept has not been embraced by the profession, despite its apparent success in some applications.

b. Abou-Seida and Saleh (1987) used the Einstein-Brown sediment transport equation and the Liu-Hwang flow resistance equation to solve for two of the dependent



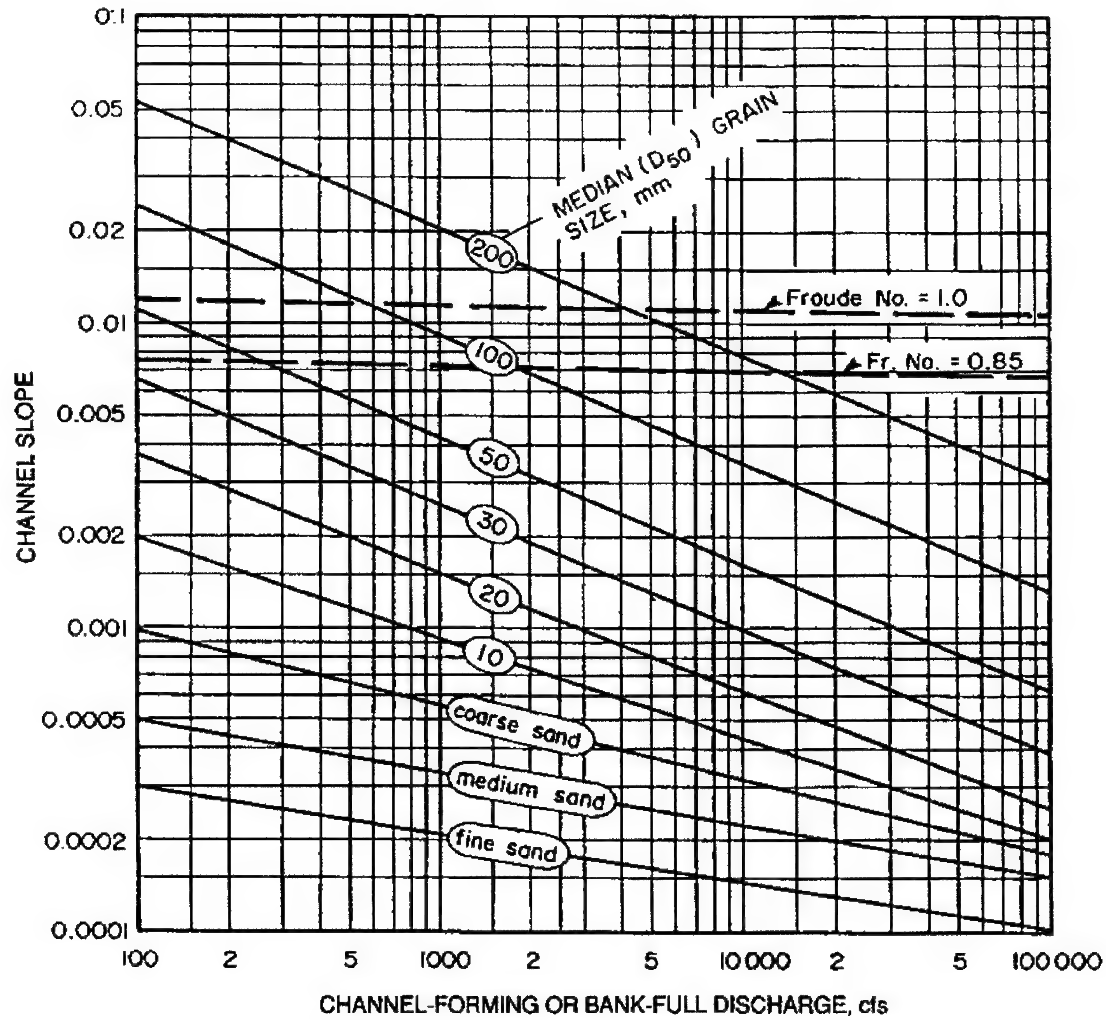
NOTE: FOR VERY APPROXIMATE GUIDANCE ONLY; DEPTHS SHOULD BE CHECKED BY UNIFORM-FLOW CALCULATION USING SELECTED WIDTH AND SLOPE (FIGURES 5-4 AND 5-5) AND ESTIMATED ROUGHNESS (SEE PARAGRAPH 4-7E).

APPLIES BASICALLY TO CHANNELS WITH LOW BED SEDIMENT TRANSPORT.

Figure 5-10. Tentative guide to depth-discharge relationships for erodible channels. See Appendix B for derivation.

design variables of width, depth, or slope, leaving one degree of freedom for the designer. Their method was developed for lower regime flow with low bed material transport.

c. The analytical stable channel design method presented in the Corps of Engineers SAM computer package for channel design calculates a family of solutions for slopes and widths that are dependent on the imposed conditions of discharge, sediment inflow, and bed material composition. This method is similar to the Abou-Seida and Saleh method in that only two of the design variables are solved for, and the designer must choose the third design variable from a family of solutions. The SAM method uses the sediment transport and resistance equations developed by Brownlie (1981). These resistance equations account for changes in roughness due to bed forms. The SAM analytical method partitions the total roughness into bank and bed resistance in the manner proposed by Einstein (1950); thus the method is not subject to the limitation of a wide channel. More detail on application of this method is available in Thomas, et al. (in preparation). An example is given in Appendix C.



NOTE: FOR LIMITATIONS SEE PARAGRAPH 5.5. CURVES ARE BASICALLY FOR SINGLE CHANNELS WITH FULLY ALLUVIAL BED BUT LOW BED SEDIMENT TRANSPORT. SLOPES MAY BE MUCH HIGHER WITH HIGH SEDIMENT TRANSPORT, ESPECIALLY WITH SAND BEDS.

Figure 5-11. Tentative guide to slope-discharge relationships for erodible channels. See Appendix B for derivation.

5-7. Sediment Transport and Sediment Budget

a. General.

(1) Many flood control channels have substantial inflows of bed sediment from upstream and from tributaries. Stability of channel cross section and profile then requires not only that the channel should resist erosion, but also that the bed sediment should be transported through the channel without deposition and loss of designed hydraulic capacity. If the channel is dimensioned for flood capacity without consideration of sediment transport continuity, it may undergo deposition until transport continuity is attained (Figure 5-12).

(2) Most sediment transport functions predict a rate of sediment transport for given hydraulic conditions, usually average cross section, slope, and depth of flow. It

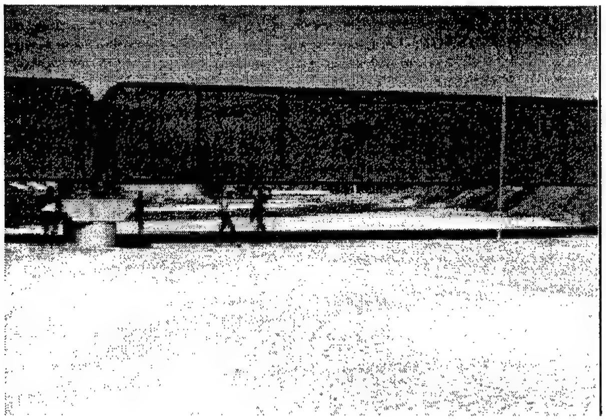


Figure 5-12. Infilling of oversized flood control channel by deposition of sand in floods

is important to know whether a given function is supposed to predict total bed material load or bed load only. For very coarse bed materials, the difference is of little significance. For sand, the suspended bed material load may be an order of magnitude greater than the bed load.

(3) It is generally agreed that "blind" computation of transport without calibration against independent data may give highly unreliable results. Different sediment transport functions were developed from different sets of field and laboratory data and are better suited to some applications than others. Different functions may give widely differing results for a specified channel. Unfortunately, acquisition of calibration data is usually very difficult. In the case of some actively shifting streams, it may be possible to make a rough check from considerations of bank erosion and bar deposition (Neill 1984, 1987).

(4) An example where computed bed load transport was compared with field measurements is shown in Figure 5-13. Bed load consisted of gravel and coarse sand and was measured across a gauging section over a period of several years using a Helley-Smith sampler (Burrows, Emmett, and Parks 1981). The data, although widely scattered, are reasonably compatible with the Meyer-Peter and Müller bed load formula, which is considered applicable to gravel channels (see Vanoni 1975).

(5) A less demanding application of sediment transport functions is to compare the computed transport capacity of a proposed modified channel with that of the original channel under a range of equivalent flow conditions, and if possible to match the curves of sediment transport versus fluid discharge. In this case absolute accuracy is not so important; however, the transport function should be selected with some care to ensure that it is not grossly inapplicable.

(6) In considering channel stability, continuity of transport over a year or more is generally more important than in one event lasting a few days or hours. To compute transport over a period of time, a transport rate versus discharge table is normally combined with a flow-duration table. It is important, however, not to overlook a large flood event. In some rivers a large flood may transport as much sediment as several years of ordinary flows.

b. Sediment budget analysis. Where field observations and checks of velocity, shear stress, or hydraulic geometry indicate a substantial degree of actual or potential bed instability and sediment transport, a sediment budget analysis may be conducted for the project reach, along the lines indicated below.

(1) Bed material transport rates are first estimated as a function of discharge using appropriate transport functions. These rates are then integrated to provide estimated total loads for two hydrologic conditions: mean annual, using the long-term flow-duration curve; and design flood, using the flood hydrograph. Each of those quantities is computed separately for both existing channel conditions and proposed project conditions. Where possible, computed loads should be checked against known quantities of erosion, deposition, or dredging over specific periods or in specific events. Otherwise, their reliability may be low.

(2) A sediment balance is then estimated for the project. The computed loads for existing conditions are assumed to represent project inflow, and those for project conditions are assumed to represent project outflow. If outflow exceeds inflow (either for the mean annual or the design flood hydrologic condition), bed erosion in the project channel is indicated. If outflow is less than inflow, bed deposition is indicated. The differential quantity can be converted to an average depth of erosion or deposition using the channel dimensions. The actual erosion or deposition will not, however, be uniform along the channel, due to slope flattening or steepening.

(3) Procedures for performing the required computations are included in the computer program "Hydraulic Design Package for Channels (SAM)" (Thomas et al., in preparation). General guidance on selection of sediment transport functions is shown in Table 5-2, and more specific guidance is included in SAM.

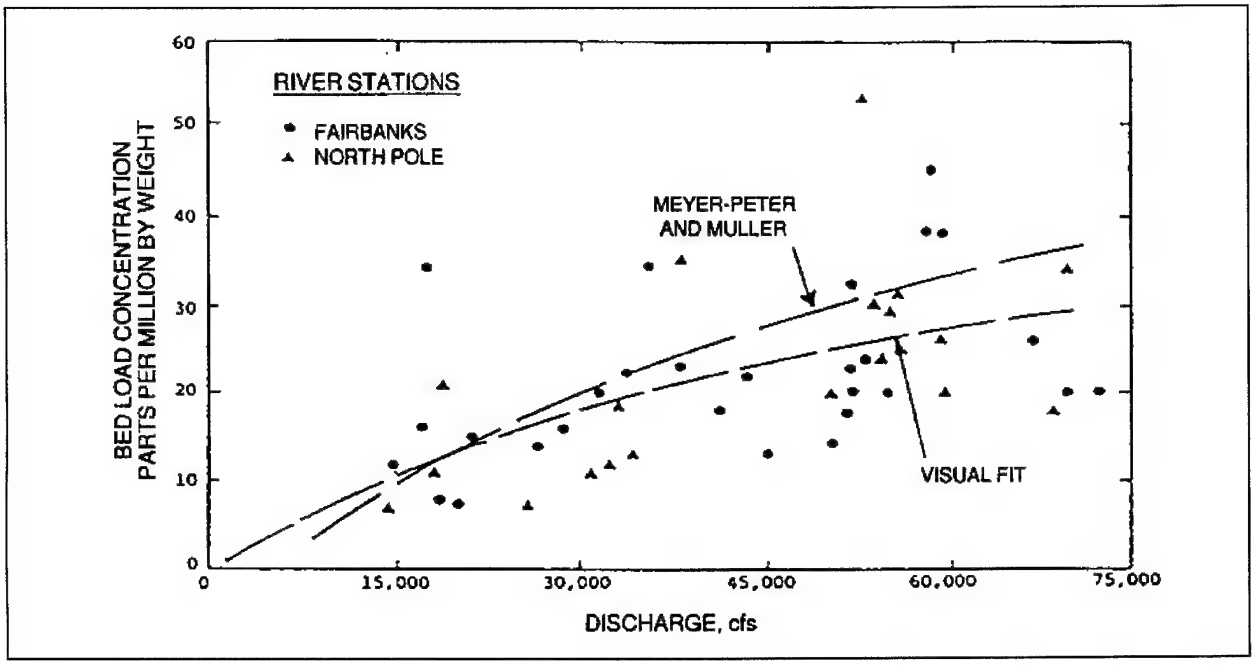


Figure 5-13. Comparison of computed and measured bed load in Tanana River near Fairbanks, Alaska (Buska et al. 1984)

Table 5-2
Sediment Transport Functions

Class of Channel	Suggested Functions	Reference
Large sand-bed rivers	Laursen-Madden Toffaleti	U.S. Hydrologic Engineering Center (1993) Toffaleti (1968)
Intermediate-size sand-bed rivers	Laursen-Madden Yang unit stream power	U.S. Hydrologic Engineering Center (1993) Yang (1973, 1984)
Small sand-bed rivers	Yang unit stream power Colby for streams with high sediment concentration	Yang (1973, 1984) Colby (1964a, 1964b)
Sand- and gravel-bed rivers	Yang unit stream power Toffaleti combined with Meter-Peter and Müller	Yang (1973, 1984) See above and below
Gravel-bed rivers	Meyer-Peter and Müller	Meyer-Peter and Müller (1948)

Note: Tentative guidance is provided below for functions most appropriate to various classes of channels. This guidance is based on experience at the U.S. Army Engineer Waterways Experiment Station and various districts, primarily with simulations involving the HEC-6 computer program. In the HEC-6 program, the functions as originally published have been modified in most cases to compute transport by size classes and to allow for high wash load concentrations where necessary. Additional guidance for selection of sediment transport functions is available in the SAM computer program package (Thomas et al., in preparation). The distinctive hydraulic variables from the user's river are compared to a large data set developed by Brownlie (1981), and a river data set is selected from a river with the most similar characteristics. The guidance program then selects a sediment transport function that best reproduces the selected data set.

(4) When application of this methodology indicates a strongly erosional or depositional situation, a more detailed sediment investigation may follow, as described in EM 1110-2-4000.

(5) Sediment budget procedures are most applicable to estimating the following types of response: profile degradation or aggradation resulting from imposed slope changes associated with realignment, or from incompatibility of existing slope with altered discharges; and erosion or deposition resulting from undersizing or oversizing of project cross sections. They are less useful for evaluating meander development and associated bank erosion and deposition.

5-8. Slope Stability

a. Bank erosion or failure often involves both hydraulic and geotechnical factors. It may be part of an overall process such as meander migration (see paragraph 2-3); it may be due to local hydraulic phenomena; or it may be due mainly to geotechnical factors like drawdown or seepage. Apparent geotechnical failure may be a delayed response to hydraulic scour at the toe. Other causes include boat-generated waves and turbulence, jams of ice or debris, and traffic of animals or vehicles.

b. Understanding of the interaction of hydraulic and geotechnical factors in streambank failure and erosion is not well developed. A number of papers under the theme "Mechanics of Riverbank Erosion" are presented in Ports (1989).

c. Mechanisms of bank slope failure in the Ohio River basin are described by Hagerty (1992). One identified process is internal erosion of sandy soil layers by groundwater outflow, followed by subsequent gravity collapse of overlying layers (Figure 5-14). Other processes referred to include erosion and infiltration of cracks by overland flow and precipitation, and river erosion of soil berms deposited by previous failures (Figure 5-15).

d. A stability analysis method for steep cohesive riverbanks (Osman and Thorne 1988; Thorne and Osman 1988) was developed from studies in the bluff-line streams of northern Mississippi but is of more general applicability. The conceived mechanism of bank failure is shown in Figure 5-15a. The analysis method is based on combining a computational model for hydraulic erosion of cohesive soil with a static analysis for gravity failure. For a particular locality with reasonably homogeneous soil conditions, a chart of critical bank height versus bank angle is developed using generalized values of local soil properties (Figure 5-15b). The chart implies that banks plotting in the unsafe zone will fail frequently, provided that fluvial activity prevents the accumulation of toe berms. Banks plotting in the unreliable zone are considered liable to failure if heavily saturated. Vegetation is not accounted for explicitly, which is admitted to be a shortcoming.

e. The above approach is most appropriate where bank failures are due primarily to geotechnical and geological factors. Where they result primarily from generalized channel processes, analysis of geotechnical mechanisms may be of secondary importance.

5-9. Meander Geometry

a. The majority of natural streams in erodible materials have more or less meandering planforms. The following points are based on extensive studies of the geometry of meanders. (For more detailed discussions see Petersen 1986; Elliot 1984; Jansen et al. 1979; Leopold, Wolman, and Miller 1964.)

(1) Meander plan dimensions are more or less proportional to the width of the river. On maps and aerial photographs, large and small rivers appear generally similar, so that the appearance of a stream gives no clue as to the scale of a map.

(2) Meander wavelength and channel length between inflection points (Figure 5-16) have both shown good correlations with channel width. Hey (1984) suggests as a preferred average relationship:

$$L = 2\pi W \tag{5-4}$$

where L is the channel length between inflection points and W is width. Hey cites theoretical support based on the size of circulation cells in bends.

(3) The ratio of radius of curvature to channel width in well-developed meander bends is generally in the range 1.5 to 4.5, and commonly in the range 2 to 3.

(4) The amplitude of meander systems is quite variable, being controlled to some extent by the valley bottom width. However, the ratio of amplitude to wavelength is commonly in the range 0.5 to 1.5.

b. The relationships cited in *a* above refer to natural streams and are not criteria for stability of flood control channels; the planforms of many meandering systems are obviously unstable. Nevertheless, the use of

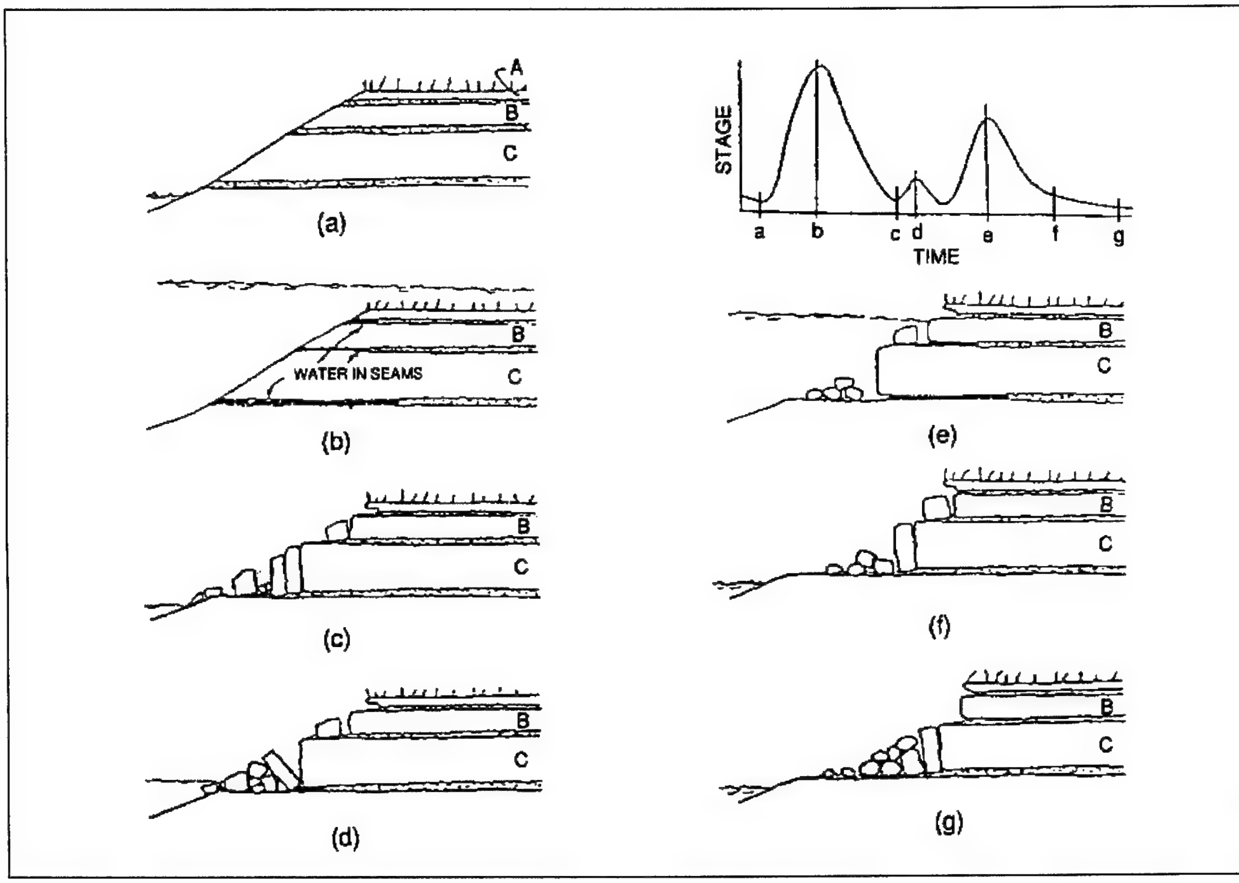


Figure 5-14. Mechanism of bank failure by internal erosion (Hagerty, Spoor, and Kennedy 1986; courtesy of University of Mississippi)

moderately sinuous rather than straight alignments is generally preferred, even where there are no existing constraints on alignment. Geometric guidelines for channel design are suggested in Figure 5-17.

c. Project changes that tend to alter channel width, mainly increased channel-forming discharges, tend also to alter meander dimensions in the course of time. Meander wavelength, like channel width, is roughly proportional to the square root of channel-forming discharge. If active meander shifting exists in the preproject channel, this is likely to continue after the project is constructed unless specific measures are taken to arrest meandering. If velocities and shear stresses are increased by the project, the rate of shifting is likely to increase.

d. It is generally observed that meander loops tend to crowd together and increase in amplitude upstream of a hard point, protected bank, or hydraulic control such as a river confluence (Figure 5-18). Where only intermittent bank protection is proposed, progressive distortion of the meander pattern may occur upstream of each protected length.

5-10. Basinwide Evaluation for System Rehabilitation

A systematic approach to stability evaluation, developed primarily by Vicksburg, the U.S. Army Engineer District, for rehabilitation of incised streams in hill watersheds of the Upper Yazoo Basin, Mississippi, involves analysis of the entire watershed to identify both local and systemwide instability problems and their interrelationships. Steps in the process include the following:

a. The entire watershed is investigated in the field to identify dominant geomorphic processes and features. (The type of information collected is indicated in Chapter 4.)

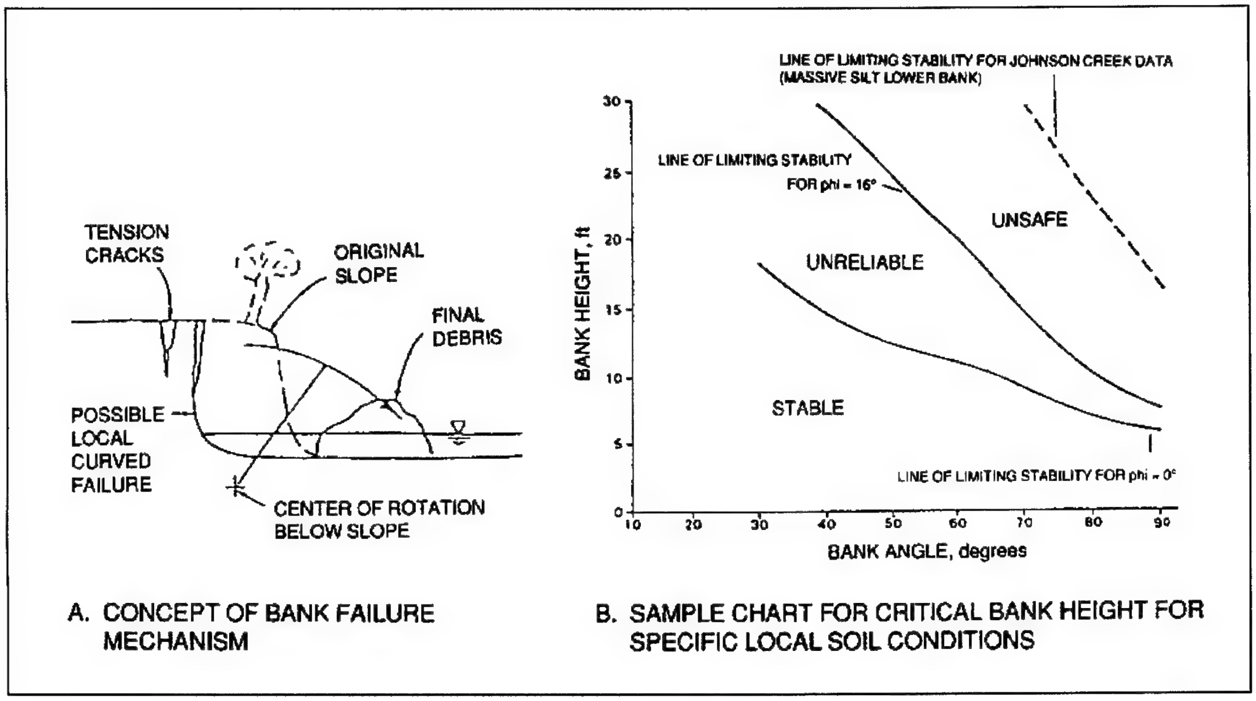


Figure 5-15. Stability analysis for steep cohesive river banks (Thorne and Osman 1988; courtesy of American Society of Civil Engineers)

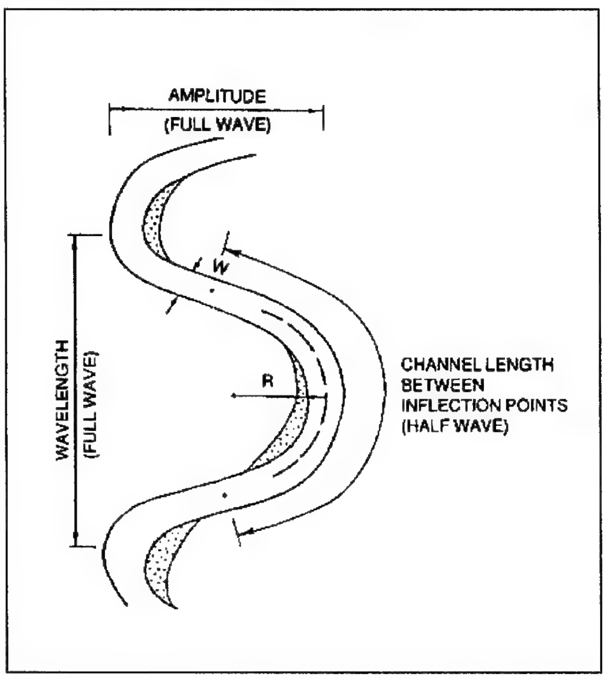


Figure 5-16. Meander geometry (after Nunnally and Shields 1985)

b. Using the information collected, an assessment is made of the system dynamics. Channels are classed as degradational, aggradational, or in equilibrium. Banks are classed as stable or unstable.

c. Hydraulic and geotechnical stability parameters are defined for reaches assessed to be stable. Generally, hydraulic parameters refer to the channel bed, for example, stable slope, boundary shear stress, or sediment transport parameters derived from modeling. Geotechnical parameters refer to the banks; they include stable bank height and angle or more complex parameters derived from detailed geotechnical analyses. For generalizing and transferring values between reaches, parameter values can be correlated with drainage area or discharge. If the watershed has subareas with different land use or geologic conditions, sets of stability parameter values may be required for each subarea.

d. Each more or less homogeneous reach of channel in the watershed is compared against the developed stability parameters and confirmed as stable, degradational, or aggradational. Additional considerations, such as the long-term effects of existing stabilization structures and anticipated changes in land use, may form part of the assessment. Anomalies within a specific reach may require further investigation.

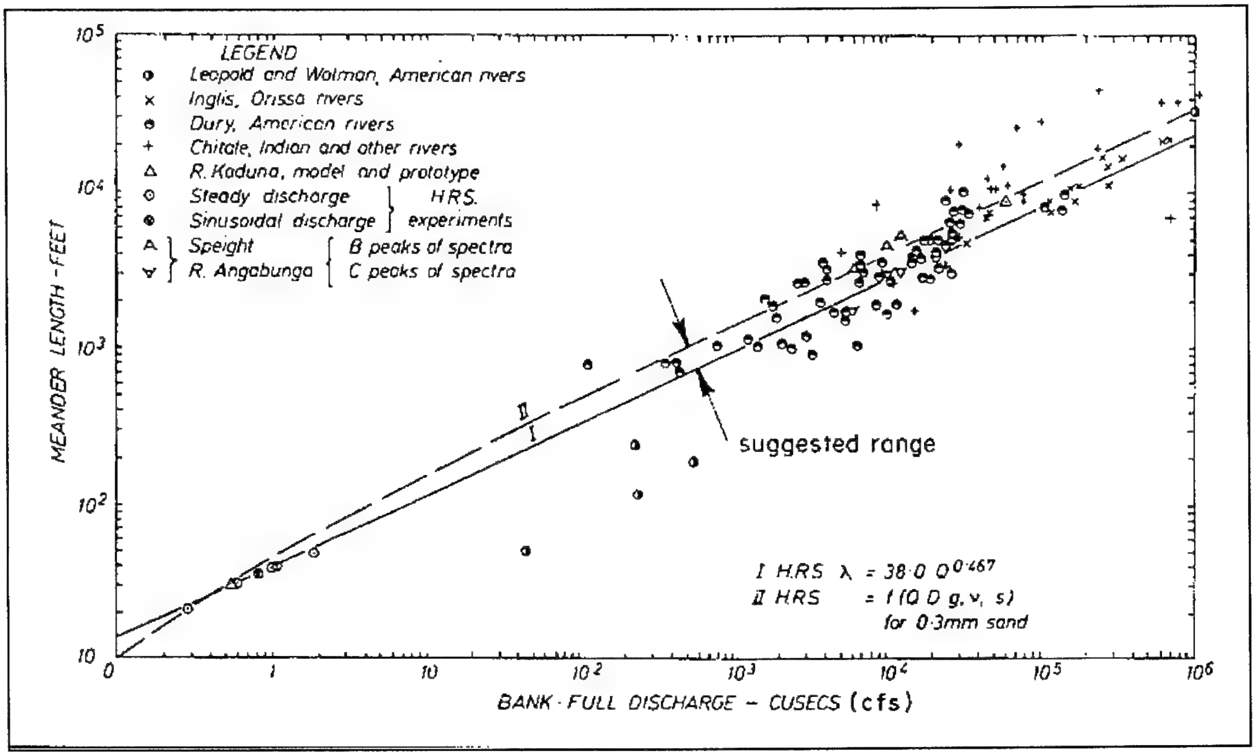


Figure 5-17. Suggested relationship between bank-full (channel-forming) discharge and meander wavelength for layout of new channel (After Ackers and Charlton 1970; courtesy of *Journal of Hydrology*)

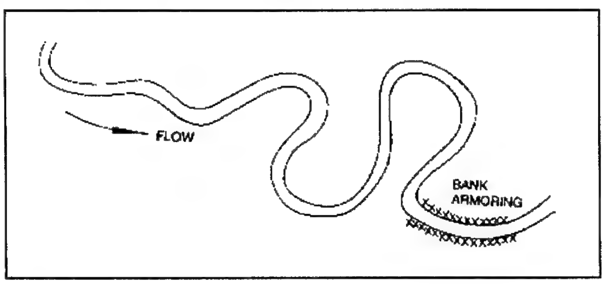


Figure 5-18. Distortion of meander pattern upstream of protected length

e. Rehabilitation measures are designed for unstable parts of the watershed and channel system. (The design of rehabilitation measures is discussed in Chapter 6.)

5-11. General Stepwise Approach

Whether or not an entire watershed needs to be evaluated, a systematic approach to evaluating and documenting the stability characteristics of the area relevant to a flood control channel project is recommended. The following sequence of steps may be found appropriate:

a. Describe characteristics of the area contributing to or affected by the project and its channel system.

b. Identify and assess existing instabilities.

c. Identify project features with stability implications.

d. Analyze stability parameters for the existing channel.

e. Evaluate and analyze potential stability problems with the completed project, and consider preventive or mitigative measures or project changes.

f. Summarize conclusions and recommendations.

5-12. Checklist of Items to Consider

The following checklist summarizes items that may be considered in a systematic stability evaluation. At each step, the investigator should consider the potentially vulnerable aspects of the system and the possibilities for

prevention and mitigation, using principles and methods outlined in this manual as well as previous experience with similar projects and environments.

a. Drainage basin.

(1) Area.

(2) Shape.

(3) Physiography.

(4) Soils.

(5) Land uses and changes therein.

(6) Erosional areas.

(7) Sediment sources.

(8) Soil conservation measures.

b. Channel system.

(1) Geomorphology.

(2) Channel types and processes.

(3) Lengths and slopes.

(4) Significance of tributaries.

(5) Historical shifts and changes.

(6) Storage reservoirs.

(7) Grade controls.

(8) Flow diversions.

c. Hydrology.

(1) Existing flow duration.

(2) Flood frequency.

(3) Historical and recent floods.

(4) Bank-full discharge and frequency.

(5) Expected project-induced changes due to regulation, diversion, reduced floodplain storage, blockage of flood escapes, land-use changes, etc.

d. Project length of channel (divided into lengths if appropriate).

(1) Plan.

(2) Cross sections.

(3) Profile.

(4) Floodplain widths and land use.

(5) Structures and crossings.

(6) Falls and nick zones.

(7) Existing flood protection and erosion protection works.

(8) Bed and bank materials.

(9) Vegetation.

(10) Roughness.

(11) Jams of debris or ice.

(12) Boat traffic.

(13) Dredging.

(14) Gravel harvesting.

e. Existing instabilities.

(1) Erosional and depositional areas.

(2) Channel processes and meander migration.

(3) Bank erosion and failures.

(4) Degradation or aggradation.

(5) Undermined or exposed or buried structures and crossings.

(6) Nick point migration.

(7) Damage by humans or animals.

(8) Channel widening or narrowing.

f. Proposed project features.

(1) Cross sections and profiles.

(2) Levees and dikes.

(3) Flood levels and velocities.

(4) Vegetation changes.

(5) Land use changes.

(6) Recreational access.

g. Potential stability problems.

(1) Initiation or aggravation of meander migration.

(2) Crossing of planform type threshold.

(3) Changes to sediment inflows or outflows.

(4) Channel widening.

(5) Bed and bank erosion.

(6) Slope changes (degradation or aggradation).

(7) Sediment deposition.

(8) Local scour and fill (e.g., at structures and crossings).

(9) Tributary degradation or aggradation.

h. Potential mitigative measures.

(1) Bank protection.

(2) Grade controls.

(3) Vegetation.

(4) Sediment and debris basins.

(5) Upstream soil conservation.

(6) Flood bypass channels.

(7) Compound cross sections.

(8) Curved alignment.

(9) Flood detention reservoirs.

(10) Sediment dredging or harvesting.

i. Conclusions and recommendations.

(1) Significance of existing instabilities.

(2) Effect of project features on instability.

(3) Implications for operation and maintenance.

(4) Need for mitigative measures.

(5) Need for more detailed analyses.

5-13. Example of Qualitative Evaluations

A qualitative example of stability evaluation is given in this paragraph to illustrate the approaches outlined in paragraphs 5-10 through 5-12. Examples of more quantitative evaluations are given in Appendix C. The following fictional example of Flatfish River near Stony Forks summarizes a qualitative evaluation conducted in 1991 at reconnaissance level, based on a review of office information and a field inspection with interviews of residents. In practice it would be accompanied by maps and aerial and field photographs, and with references to previous reports and other sources of information. It is envisaged as a presentation of information at an early stage in project formulation.

a. Description of project-related area and channel system.

(1) Project length: 10 miles.

(2) Drainage basin.

(a) Dimensions: area 500 square miles, 40 miles long by 18 miles wide maximum.

(b) Physiography: low hills with alluvial valley.

(c) Geology: residual and alluvial soils over weak bedrock (sandstones and shales).

(d) Land use: hills wooded, valley in mixed woodland and farms, history of land clearing, recent encroachment of residential acreages.

(e) Sediment sources: surface erosion from recent logging in upper basin, high bank erosion in some tributary hill streams.

(3) Channel system.

(a) Upstream of project, main stem and tributaries are mostly incised with occasional bedrock outcrops. Some tributaries deliver quantities of fine and coarse sediment. No storage reservoirs. Minor irrigation diversion with weir just upstream of project length.

(b) In project length, Flatfish River flows in broad alluvial valley through mixed farmland and residential acreages. Channel partly single and partly double with islands. Floodplain both sides except at occasional points of impingement on valley margins. Probably underlain by considerable depths of alluvium in most areas.

(c) Downstream of project length, Flatfish gradually changes to a meandering sand river, and discharges into a larger river 20 miles downstream. There are only a few minor tributaries.

(4) Flood hydrology: no hydrometric data or simulation studies are available for Flatfish River. Regional correlations suggest mean annual flood around 1,200 cfs and 50-year flood around 3,500 cfs. Largest known flood occurred in 1962 and most recent overbank flood in 1988. 1962 flood caused \$10 million damage to crops and buildings, and 1988 flood \$20 million mainly to residences. Extensive residential development occurred between 1962 and 1988.

(5) Project length of river.

(a) Planform. Irregular meanders with splitting around islands. Meanders typically about 1,000-ft wavelength by about 500-ft full-wave amplitude. Comparison of 1984 and 1950 aerial photos indicates substantial channel migration, and trend to wider channel with more exposed bars.

(b) Profile. Average slope 8 ft per mile. Sequence of pools and riffles at low flow. No visible rock rapids or nick zones. Narrow bridge at lower end may cause backwater effect at high flows.

(c) Cross sections. Typical bank-full section (in single-channel reach) about 70 by 4 ft, but considerable variability. Summed width of double reaches about 100 ft. Summed floodplain width (both sides) 500 to 1,500 ft. Floodplain cover about 40% grass, 30% crops, 30% trees. Overbank flow about once every 2 years, allegedly more frequent than in past. No existing flood protection dikes.

(d) Boundary materials. Bed: sand and gravel up to 50 mm. Channel bars variable in form and in surface grain sizes. Banks stratified: 1 to 2 ft overbank silt and fine sand overlying medium sand and gravel. Banks mostly cleared of vegetation except through wooded floodplain areas. Some local bank protection of limited effectiveness using timber piles and car bodies. Some complaints of accelerated erosion due to protection of neighboring properties.

(e) Miscellaneous observations. Water is clear in low flow, turbid in floods. Gravel moves actively on bars under moderate flows. Log debris on some bars and islands. Alleged adverse effects from logging in upper basin. Some winter ice but no effects on channel stability. No significant boat traffic. No local flood control on similar streams.

b. Existing instabilities.

(1) Drainage basin. Basin land use changes may have somewhat increased flood peaks, sediment loads, and debris. An apparent trend of increasing channel instability may continue. There are no plans for controlling basin erosion, which is not considered a major problem.

(2) Channel system. Outside the project area, it has not been examined in detail. Superficially there appear to be no major upstream instabilities. Any change in sediment deliveries to downstream reaches would be of concern to fishery authorities.

(3) Project channel. Substantial lateral instability: eroding banks, loss of land, mobile channel bars. Aerial photos suggest bank recession rates up to 5 ft per year, residents allege even higher local rates. A supply of coarse sediment enters the length from upstream. No evidence of profile instability: bridge foundations near either end show no indication of degradation or aggradation. Some apparent increase in average width since 1950 aerial photos. Only isolated local attempts to control bank erosion.

c. Analysis of stability parameters. This step is omitted in this qualitative evaluation. See quantitative examples in Appendix C.

d. Stability implications of project features. The proposal is to construct levees on both sides of the

channel, to contain floods up to the 50-year level. Riparian owners would like the levees to be close to the riverbanks and assume that there would also be bank protection. Project details have not been determined.

e. Assessment of potential stability problems with proposed project.

(1) Altered flood hydrology. Levees close to the river would probably increase flood peaks to some degree because of the deregulating effect of eliminating floodplain storage. This effect can be reduced if the levees are set back. Surveys and hydrologic/hydraulic analyses would be required to examine these effects.

(2) Lateral instability. Existing lateral instability poses problems for close-set levees. Substantial setback is indicated to avoid excessive bank protection costs. Increased in-channel flow peaks may tend to increase lateral instability and sediment supply to downstream. Erosion protection of river banks or levee faces may be required at least locally.

(3) Profile instability. Some flattening of slope may be expected because of increased in-channel flood peaks, but process is likely to be slow and controlled by armoring of bed material. Grade controls could be installed at a later stage if a problem develops.

(4) Cross-sectional instability. There may be a tendency for cross sections to widen and possibly deepen eventually, because of increased in-channel flood peaks. This is unlikely to be of serious concern under present development.

f. Summary.

(1) A workable scheme for 50-year flood protection can be developed. The existing channel is laterally unstable and is liable to encroach on levees located near the channel. Because it eliminates much floodplain storage and increases in-channel flood peaks, the project may aggravate meander shifting and alter channel properties somewhat. Potential maintenance problems include bank protection to secure the levees and increased delivery of sediment to downstream reaches.

(2) Further studies should consider a range of solutions to the flooding problem. Any solution involving levees should recognize the effects of existing and possibly enhanced instability on the security of the levee system, and should provide for adequate protection against erosion or undermining.

Chapter 6
Practical Aspects of Stability Design

6-1. General

This chapter provides guidance and examples for various practical aspects of design for stability. The main causes of the type of instability to be controlled are reviewed briefly in each case. General principles of channel equilibrium and response are reviewed in Chapter 2. Stability problems with flood control channels are discussed in detail in Chapter 3.

6-2. Ranking of Flood Control Methods

From the viewpoint of minimizing channel stability problems, methods of flood control can be generally ranked in the following order of acceptability:

a. Nonstructural flood control measures such as floodproofing, evacuation, and flood warning systems.

b. Levees set back clear of the meander belt.

c. Levees within the meander belt.

d. Off-channel detention basins.

e. Upstream flood retention or detention structures.

f. Flood bypass channel.

g. Clearing and snagging (reduced roughness).

h. Enlarged compound cross section with existing low-flow channel left intact. (The low-flow channel carries average dry-season flow.)

i. Channel widening with or without levees.

j. Channel deepening with or without levees.

From a safety viewpoint, on the other hand, channelization measures like *h* and *i* above tend to be more defensible than structural measures such as *b*, *c*, and *e*. Potential conflicts between stability and safety requirements should be discussed with local interests and considered together with economic, social, and environmental factors. Table 6-1 shows the potential for several flood protection measures to cause instabilities in various types of river channels.

6-3. Alignment and Planform

Earlier flood control projects often involved extensive realignment of pre-existing streams and channels. Sinuous or meandering channels were straightened to improve hydraulic conveyance or to eliminate eroding bends, often without sufficient consideration of potential effects on long-term stability. Severe instability in profile and cross section often occurred in and beyond the project length, and the treated length of channel often reverted eventually to a meandering state unless expensive remedial measures were undertaken (Figure 3-6).

6-4. Single-Channel Streams

a. Most existing channels are sinuous to some degree. Current practice is generally to retain existing alignments where practicable. Even where an entirely new channel is to be constructed, arguments can be made for a sinuous rather than a straight alignment. Keller and Brookes (1984) state "Consideration of meandering in channelization projects should be encouraged wherever feasible because meandering channels often have a more consistent pattern of sediment routing, are morphologically more stable, have more hydrological and biological diversity, and aesthetically are more pleasing." Similar comments are made by Nunnally and Shields (1985). Flood control channels stabilized on meandering alignments are shown in Figures 6-1 and 6-2. Points that can be made in support of sinuous alignments include the following:

(1) Retention of a sinuous alignment avoids problems of excessive slope associated with straightening.

(2) Straight channels transporting bed material tend to form alternating side bars that induce submeandering in the low-flow channel (see Figure 3-2). This may eventually lead to resumption of full-scale meandering.

(3) Sinuous channels have greater local variability of depth, velocity, and cross-sectional shape, which is attractive for fish habitat.

b. Where a sinuous alignment is retained, however, it may be appropriate to eliminate or improve severe bends that are subject to rapid bank erosion and flow disturbances (Figure 6-3). Where the channel is widened by side cuts on alternating sides, the sinuosity can thereby be reduced to some degree (see Figure 3-3).

Table 6-1
Rating of Flood Control Measures for Channel Stability

Flood Protection Measures	Channel Types[*]									
1. Non-structural: floodproofing, flood warning, evacuation.	0	0	0	0	0	0	0	0	0	0
2. Levees: set beyond stream meander belt.	1	2	2	1	1	1	1	2	1	1
3. Levees: set within stream meander belt or along bankline.	2	5	5	4	3	3	2	4	2	2
4. Off-channel flood detention basin.	2	3	3	3	2	2	2	2	1	1
5. Within-channel flood detention basin.	4	5	5	5	4	4	3	4	2	2
6. Major flood storage reservoirs.	3	4	4	4	3	3	2	3	1	1
7. Floodway, diversion, or bypass channel.	4	5	5	5	4	4	4	5	3	3
8. Compound channel - low-flow pilot plus flooding berms.	5	8	8	7	7	6	6	7	4	4
9. Significant channel widening.	6	9	9	8	8	6	7	7	5	5
10. Significant channel widening and deepening.	7	9	9	9	9	8	8	8	6	7
11. Significant channel widening, deepening, and straightening.	8	10	10	10	10	8	9	9	7	8

No Stability Impacts 0 2 4 6 8 10 Major Impacts On Stability
|..|..|..|..|..|..|..|..|..|..|

----------- Channel Stability Rating Scale --------------

[*]Note: See paragraph 2-2 for a complete description of the channel types.

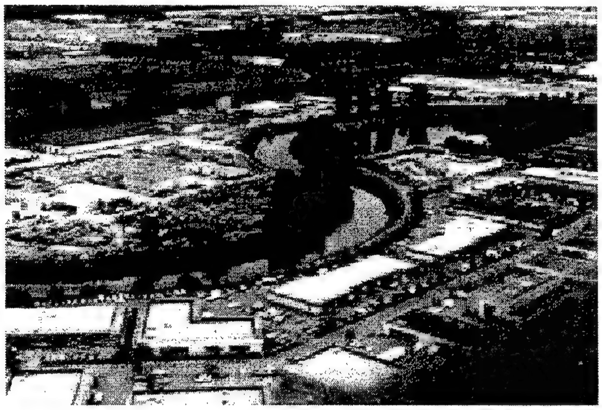


Figure 6-1. Regulated river with levees on meandering alignment

c. Generally accepted standards for the layout of new sinuous channels are not available. A general principle that can be followed is to match the wavelength to that of a corresponding natural meandering channel, that is, a stream in similar soils with similar channel-forming discharges. Relationships between meander wavelength and channel width are discussed in paragraph 5-9. A suggested relationship between meander wavelength and bank-full (channel-forming) discharge is shown in Figure 5-17.

d. In the absence of generally accepted guidelines for radius of curvature and deflection angle, it is suggested that where possible, radius of curvature should be at least five times the channel width, and that the deflection angle of a single bend should not exceed 90 degrees. Natural streams often have tighter meander curvature (paragraph 5-9).

6-5. Multichannel Streams

a. Some streams consist of two or more subchannels over substantial parts of their length. Examples include the Snake River near Jackson Hole, Wyoming, as described in paragraph 3-12 and the Tanana River at Fairbanks, Alaska, as described in paragraph 3-17. Braided rivers (Figure 2-5) constitute a limiting case.

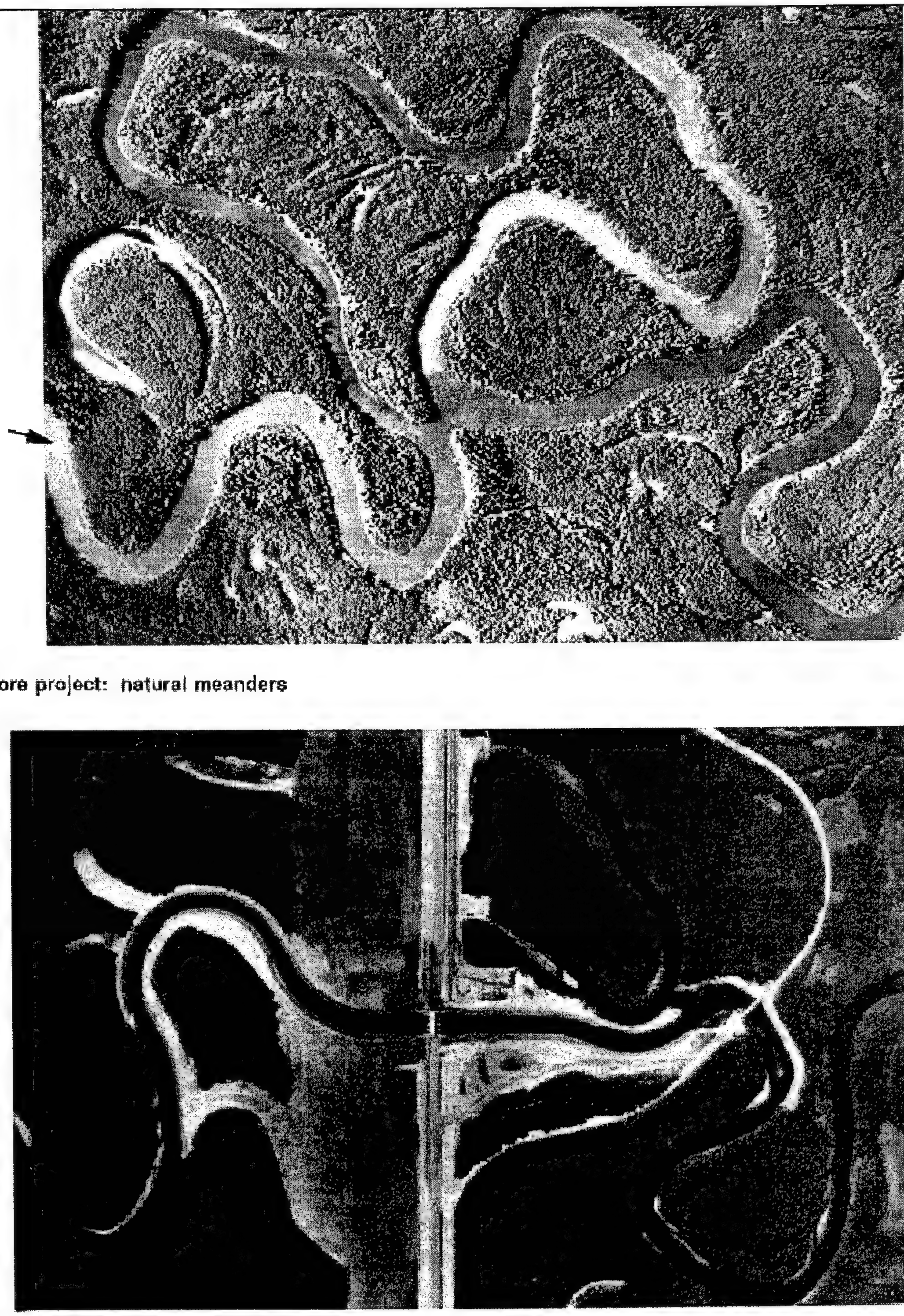
b. In modifying a multichannel stream to increase its flood conveyance, various alternatives might be considered, as illustrated in Figure 6-4. Alternative A (Figure 6-4a), involving levees set well back from the active channel shift zone, is usually the most economical and least troublesome to maintain. Alternative B (Figure 6-4b) is likely to be the most expensive because deep scour may have to be provided for at any point along the levees. Alternative C (Figure 6-4c), although it may appear desirable because it reclaims more land from the river, is liable to raise flood stages and to meet with environmental objections. However, each case should be examined on its merits. Detailed study of historical maps and aerial photographs may reveal that the shift pattern is more predictable than it first appeared to be.

6-6. Alluvial Fans

a. The general characteristics of alluvial fans are described in paragraph 2-2. A typical residential development on an alluvial fan in California is illustrated in Figure 2-4. In considering the location and alignment of flood control channels, it is important to determine whether the fan is actively aggrading or whether it is in a stable or degrading state geomorphologically. If the fan surface is generally unvegetated and the principal channel spills easily and is "perched" in relation to ground at equal distances from the apex (Figure 6-5), the fan is likely to be actively aggrading. On the other hand, if the surface is generally well vegetated between channels and the main channel is well incised, the fan may be stable or even degrading.

b. On aggrading fans, developments requiring flood protection should often be discouraged because expensive flood control structures and ever-increasing maintenance may be required to keep the flow in the existing main channel or channels as their bed levels build up with deposited bed material. If the existing main channel is perched, it may be preferable to select a lower initial route or fall line for the flood control channel. It should be recognized that selected routes may not be maintainable indefinitely because of constraints on maintenance, especially during flood events, and because on some fans, the risk of catastrophic flood-debris events can be much more severe than previously observed floods. If development proceeds with recognition of risks, consideration may be given to sediment control features including debris basins and concrete linings, as discussed in paragraph 6-7*c* below. On an alluvial fan, a debris basin would normally be located at the head of the fan, unless the main sediment supply is located farther downstream (Figure 6-6).

c. On stable or degrading fans, problems of alignment and planform are essentially those of multichannel streams. In some cases it may be desirable to construct levees along the route of the main channel, closing off



a. Before project: natural meanders

b. After project (diversion structure and channel): controlled meanders

Figure 6-2. Construction of a meandering alignment

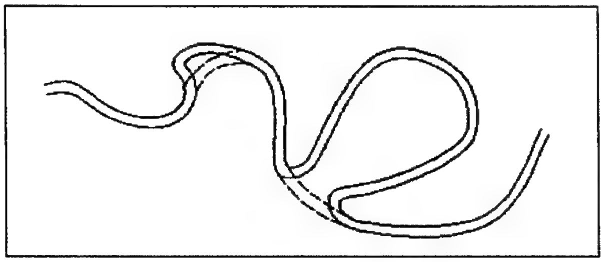


Figure 6-3. Alignment modifications to eroding bends

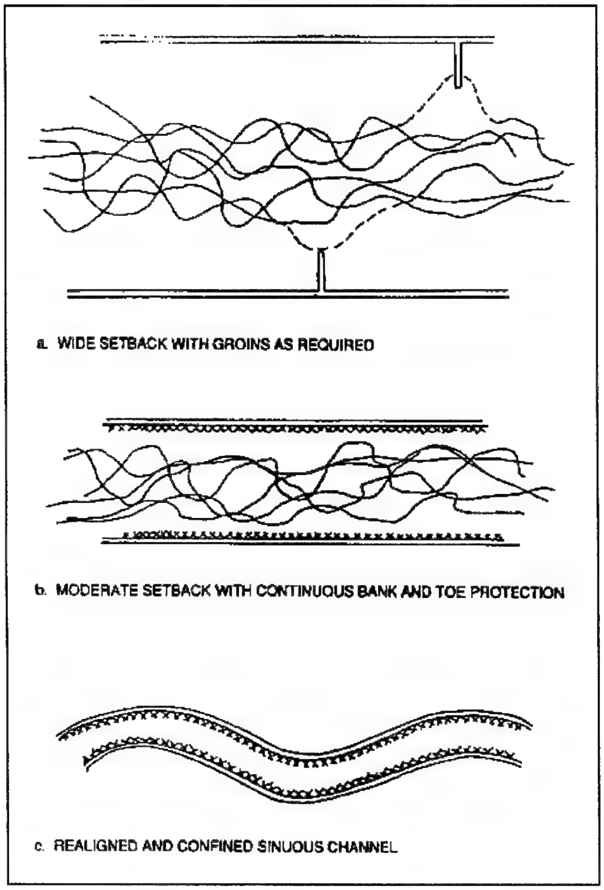


Figure 6-4. Alternative levee locations along braided channel

secondary channels or retaining them as escape routes for spills at designed low points in the levee system.

d. In some places where development has occurred on closely adjacent alluvial fans (piedmonts or bajadas) all issuing from the same mountain range, cross-slope interceptor channels have been used to pick up flows from a series of fans and lead them to the main channels (Figure 6-7). In the case illustrated, debris basins are located at the head of each fan (see paragraph 6-7*c*).

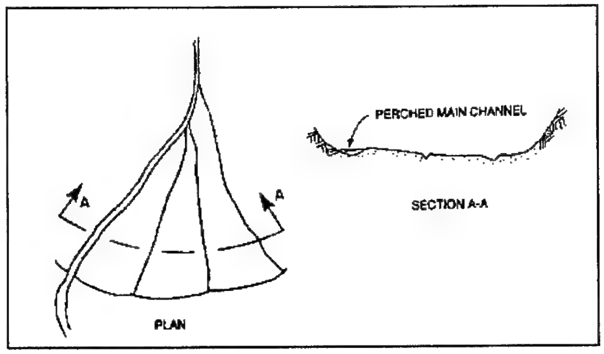


Figure 6-5. Perched channel on aggrading alluvial fan

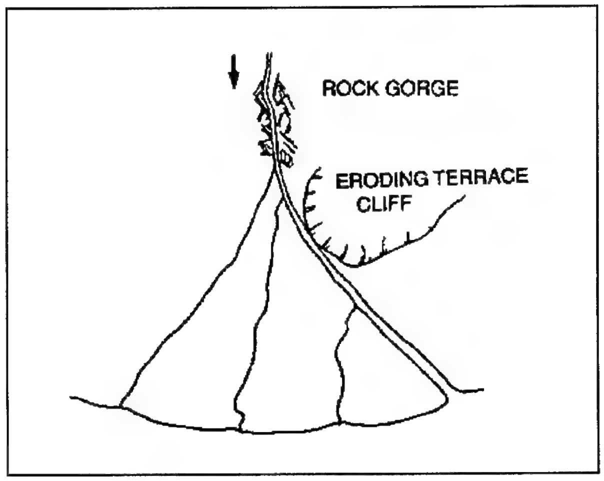


Figure 6-6. Principal active source of fan bed load may be downstream of apex

6-7. Longitudinal Profile and Grade Controls

a. Causes of profile instability.

(1) In most cases the basic longitudinal profile of a flood control channel is determined by the slope of the existing channel. Most problems of longitudinal instability arise because the existing slope is too steep for equilibrium under the modified sedimentation, hydraulic, or hydrologic conditions of the flood control channel. The bed of the project channel then begins to degrade within and upstream of the project length, and perhaps to aggrade downstream.

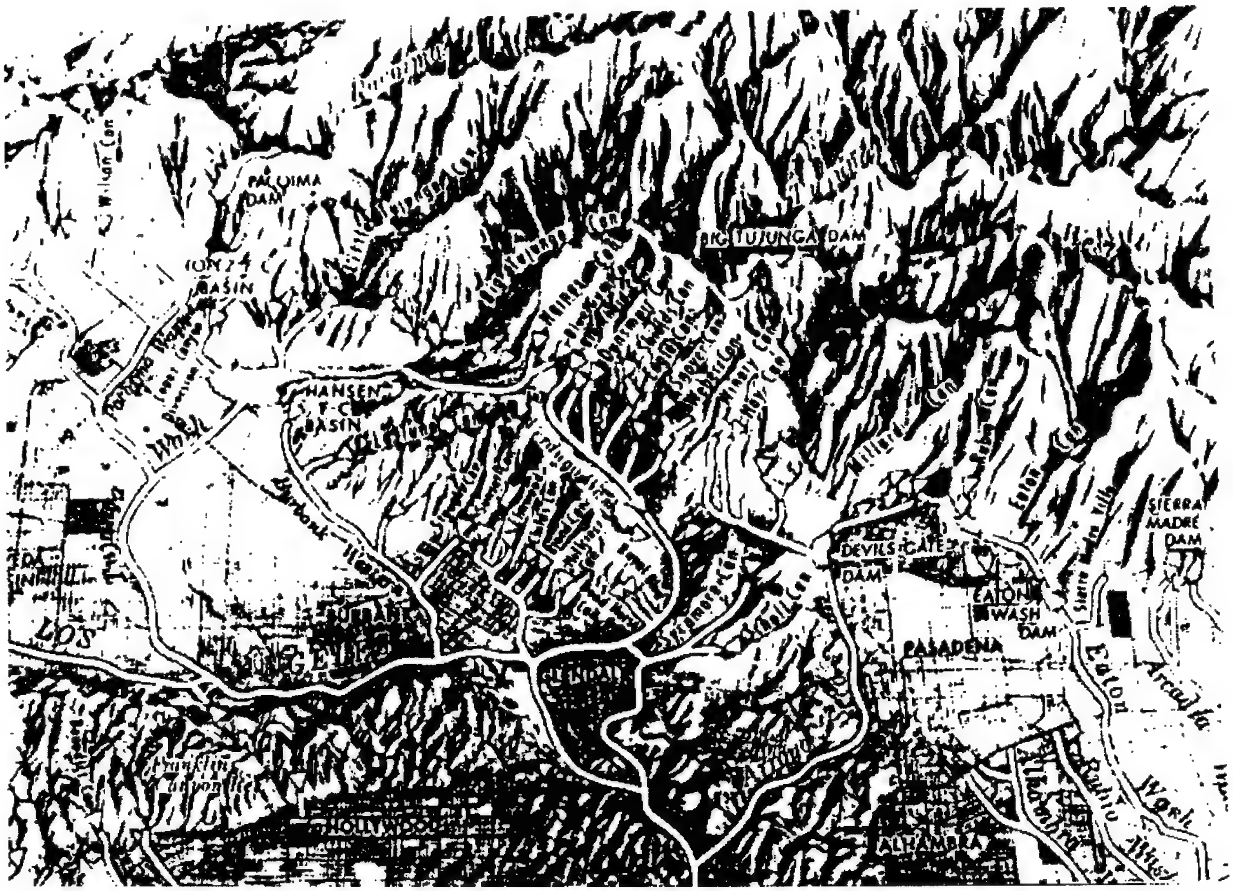


Figure 6-7. Cross-slope interceptor channels collecting flood flows from adjacent alluvial fans

(2) There are two main reasons the existing gradient may be too steep for the project channel. The first reason is that discharges in the project channel may be significantly larger than in the existing channel. As explained in Chapter 2, larger discharges require flatter slopes to maintain equilibrium with equivalent bed material transport; see also Figure 5-11. A second reason is shortening through realignment, which was a common problem in earlier flood control projects but is now discouraged, as discussed in paragraph 6-4. A third, less common reason may be the addition of a basin or reservoir that traps bed material upstream of the project channel (paragraph 6-6).

(3) Problems of profile degradation are most common and severe in channels with beds of sand or other easily eroded fine-grained materials. Examples include many of the bluff-line streams of northern Mississippi, which as a result of land-use changes and channel alterations are generally degrading into fine-grained deposits of sand, loess, silt, and clay. In gravel-bed channels, the ability of the stream to armor the surface of the bed with the coarser fraction of the bed load tends to retard rates of degradation.

(4) An opposite type of longitudinal stability problem arises when the project channel slope is too flat and begins to steepen (aggrade) by accumulation of bed material. This can occur in diversion and bypass projects if flows in the existing channel are thereby reduced but the channel continues to take a substantial part of the bed material load (see also Chapter 3, Section I). This type of problem may also arise in new channel projects if the slope provided is insufficient to transport all the inflowing bed material.

b. Grade control structures.

(1) Channel profile degradation can be controlled by the use of grade control structures at intervals along the channel. Grade control structures provide local hard points or controlled drops so that an equilibrium slope can develop or be constructed between structures (Figure 6-8). The spacing is determined so that the local degradation or drop below each structure is within acceptable limits. Acceptable limits depend on economic, environmental, and other considerations.

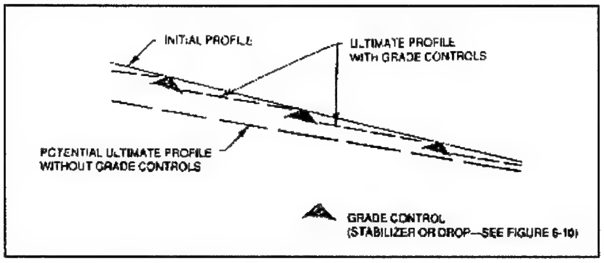


Figure 6-8. Use of grade controls to limit profile degradation and downstream sedimentation

(2) The basinwide evaluation approach referred to in paragraph 5-10 can be used to assess the need for grade control and to determine the appropriate design for achieving stable channel slopes and bank heights.

(3) The rating curve of a grade control structure should normally be designed to match that of the upstream channel as closely as possible over the full range of discharges. In some cases, stepped sill crests are used to achieve a match (Figure 6-9). It may be desirable in incised streams to construct the grade control to act as a weir at an elevation above the preproject channel bottom. Such a structure would tend to trap sediments, flatten channel gradients, lessen bank heights, and promote the overall stability of the channel system.

(4) The decision as to whether grade controls or drops should be part of the project design or whether they should be deferred until problems develop depends partly on economic and political considerations and partly on the expected severity of profile response. Previous local experience is generally valuable in making this determination. However, the entire channel system should be reviewed, including tributaries and their expected reaction to flood control on the main stem. If degradation of the main stem or tributaries is projected, grade control features should be used as part of the initial project.

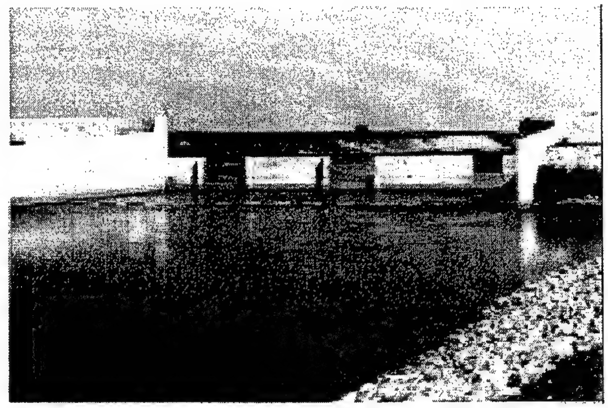


Figure 6-9. Use of stepped sill on grade control structure to match upstream rating curve

Construction should be phased so that tributary grade control features are completed before flow line lowering on the main stem.

(5) Grade control structures are generally classified into two types: stabilizers and drop structures (Figure 6-10). The distinction between the two types is not always clearcut. Design guidelines for both types are given in EM 1110-2-1601 and in Hydraulic Design Criteria 623/624, and have been expanded by Robles (1983).

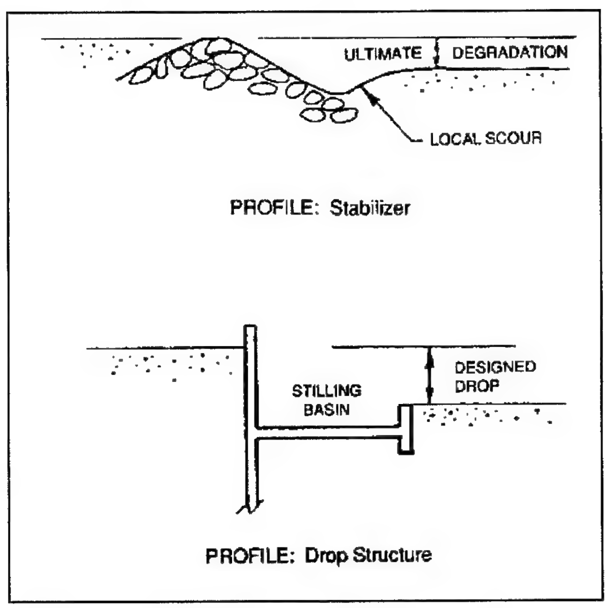


Figure 6-10. Classification of grade control structures

According to Robles (1983), stabilizers as used in the U.S. Army Engineer District, Los Angeles, are "concrete or grouted stone sills built across the channel to form an artificial control point." Stabilizers may be of three types: weirs, chutes, or flumes, and may be constructed of a wide variety of materials. Types illustrated include a simple sheet pile weir (Figure 6-11) and a special flume type developed in Mississippi (Figure 6-12). If the drop that develops below a stabilizer is too great—normally 2 to 4 ft depending on type—energy dissipation becomes a problem and more elaborate drop structures must be used. Drop structures are normally provided with some form of stilling basin or armored plunge pool for energy dissipation (Figure 6-13). They have been used as remedial measures in cases of severe degradation, or as elements of project design where substantial slope flattening is expected. Whether to use stabilizers at relatively close spacing or drop structures at wider spacing is partly an economic question.

(6) Where existing slopes are only marginally excessive, it may be possible to achieve longitudinal stability by increasing channel roughness, for example using scattered boulders placed in a manner to prevent them from sinking into their own scour hole. Such a solution is often favored by fisheries interests as it provides useful resting places and shelter.

c. Control of sediment inflows.

(1) Some flood control channel projects may require special features for control of sediment inflows, in order to reduce the need for future dredging to maintain flood capacities and tributary access. Channels on aggrading alluvial fans, as referred to in paragraph 6-3, provide one example. Increases in sediment inflow due to expected degradation of the upstream channel or tributaries can often be controlled through grade control structures as described in paragraph 6-2 above. However, other means to control sediment inflows, such as sediment or debris basins, may also be desirable. Sediment basins are commonly used at the heads of alluvial fans (Figure 6-14).

(2) In the Yazoo Basin in Mississippi, combinations of grade control structures, artificial sediment basins, and natural sediment trapping areas have been used for effective control of anticipated maintenance dredging requirements. The grade control structures have raised sills to build up existing degraded channel beds. Sediment basins within the leveed floodway also provide a source of levee borrow material. Sediment trapping areas are naturally low lands in or near certain reaches of channel. All these features provide incidental environmental benefits by improving water quality, reducing disturbance by future maintenance work, and enhancing fish and wildlife habitat.

(3) Another means of controlling sediment inflows in small watersheds is to provide grade control or riser pipe structures on the small tributaries. These structures detain small volumes of flood water and allow deposition of coarser sediments in a designated area. They can also prevent the upstream migration of head cuts and gullies. A typical riser pipe structure as used in the Yazoo Basin is shown in Figure 6-15.

(4) Where an unlined flood control channel is expected to lose capacity due to deposition of bed material from sediment inflows, and where sediment basins or maintenance dredging appear impracticable, it may be advisable to consider a lined channel for high-velocity flow and sediment flushing. Lined channels may also be used downstream of a debris basin to prevent bed degradation (Figure 6-16). Some data on sediment transport and self-cleaning velocities in lined channels are provided by Mayerle, Nalluri and Novak (1991). However, lined channels are not always free from sediment problems. In Corte Madera Creek, California, where gravel deposited in the downstream reaches of the concrete-lined channel, the Manning roughness coefficient was found to be 0.028 (Copeland and Thomas 1989).

(5) Recent flume experiments at WES showed that near-bottom coarse sediment concentrations of 3,000 ppm increased roughness values by about 10 percent (Stonestreet, Copeland, and McVan 1991).

6-8. Cross Sections and Hydraulic Capacities

a. Range of cross-sectional types. A wide variety of cross-sectional types and modifications have been used in flood control channel projects. The following types are illustrated in Figure 6-17:

(1) Existing channel retained, with wide setback levees on floodplain.

(2) Existing channel retained, with levees close to channel banks.

(3) Channel widened on one or both sides to full depth.

(4) Channel deepened and widened on one side.

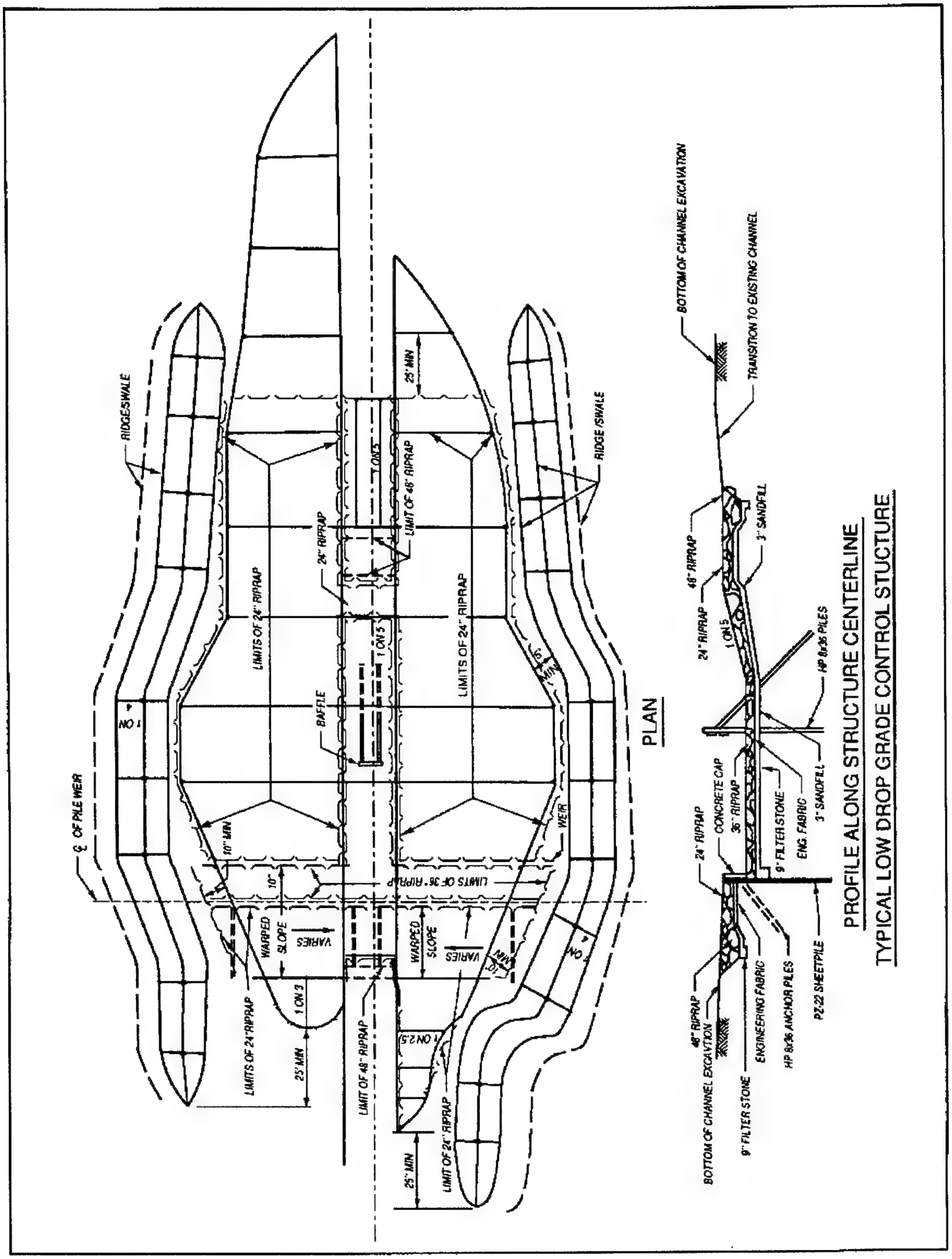


Figure 6-11. Sheet pile weir stabilizer

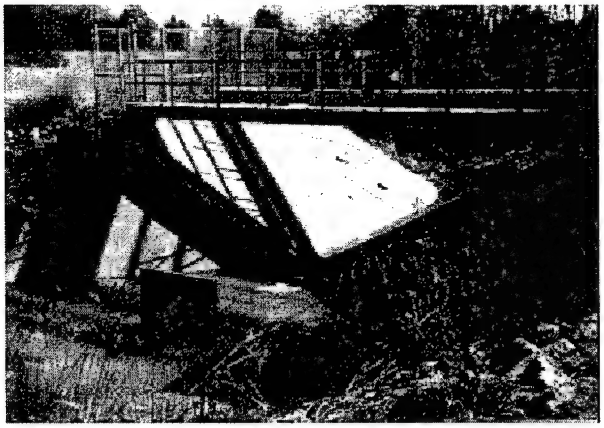


Figure 6-12. Flume-type grade control/gauging structure

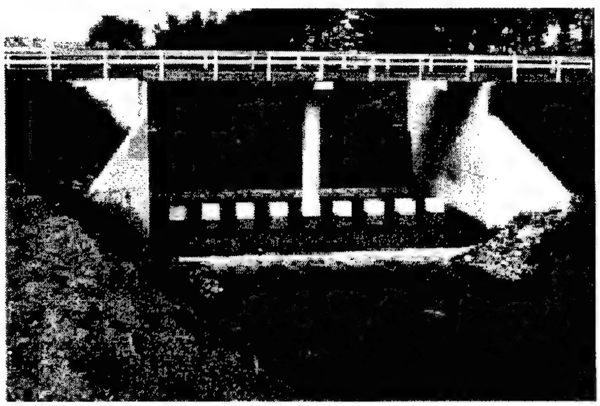


Figure 6-13. Drop structure with energy dissipator

Figure 6-14. Debris basin and dam at head of alluvial fan

(5) Channel deepened and widened to part depth (with berm).

(6) Major enlargement with retention of inner low-flow channel (Figure 6-18).

(7) Existing channel paralleled by separate floodway or bypass channel.

b. A number of these alternatives are also discussed in paragraphs 3-1 and 6-2. From a stability viewpoint Type a is generally preferable, but in many cases other considerations will predominate. Type g is also attractive if sedimentation is not a problem (paragraph 3-7). Generally, widened and deepened sections are the most susceptible to problems of bank erosion, channel shifting, and profile degradation.

c. A wide variety of practices exist for determining channel capacity and frequency of the bank-full condition, depending on the overall requirements of the project. In compound cross sections such as type *e*, the berm level normally corresponds to the annual summer flood. In type *f*, the low-flow channel may be sized for dry-season flows only.

d. Increasing channel capacity in environmentally sensitive areas.

(1) A problem facing many Corps Districts is design of flood control projects in river basins or specific reaches of river basins that are extremely environmentally sensitive. Increased channel conveyance can often be achieved in these areas through either clearing and snagging or channel cleanout alternatives. These alternative channel improvement methods, both of which are generally much less destructive to the environment than conventional channel enlargement, are defined in (2) and (3) below. (See also paragraphs 3-2 and 3-3.)

(2) Clearing and snagging. Channel clearing and snagging (Figure 6-19) involves the removal of trees, brush, logjams, and other material from the channel. Channel capacity is increased as roughness is reduced and blockages removed. Work is typically limited to within the top bank of the channel but may be extended to the overbank if significant overbank flow occurs and the work is environmentally acceptable. The degree of improvement can range from total clearing where all woody vegetation is removed from the channel to selective clearing

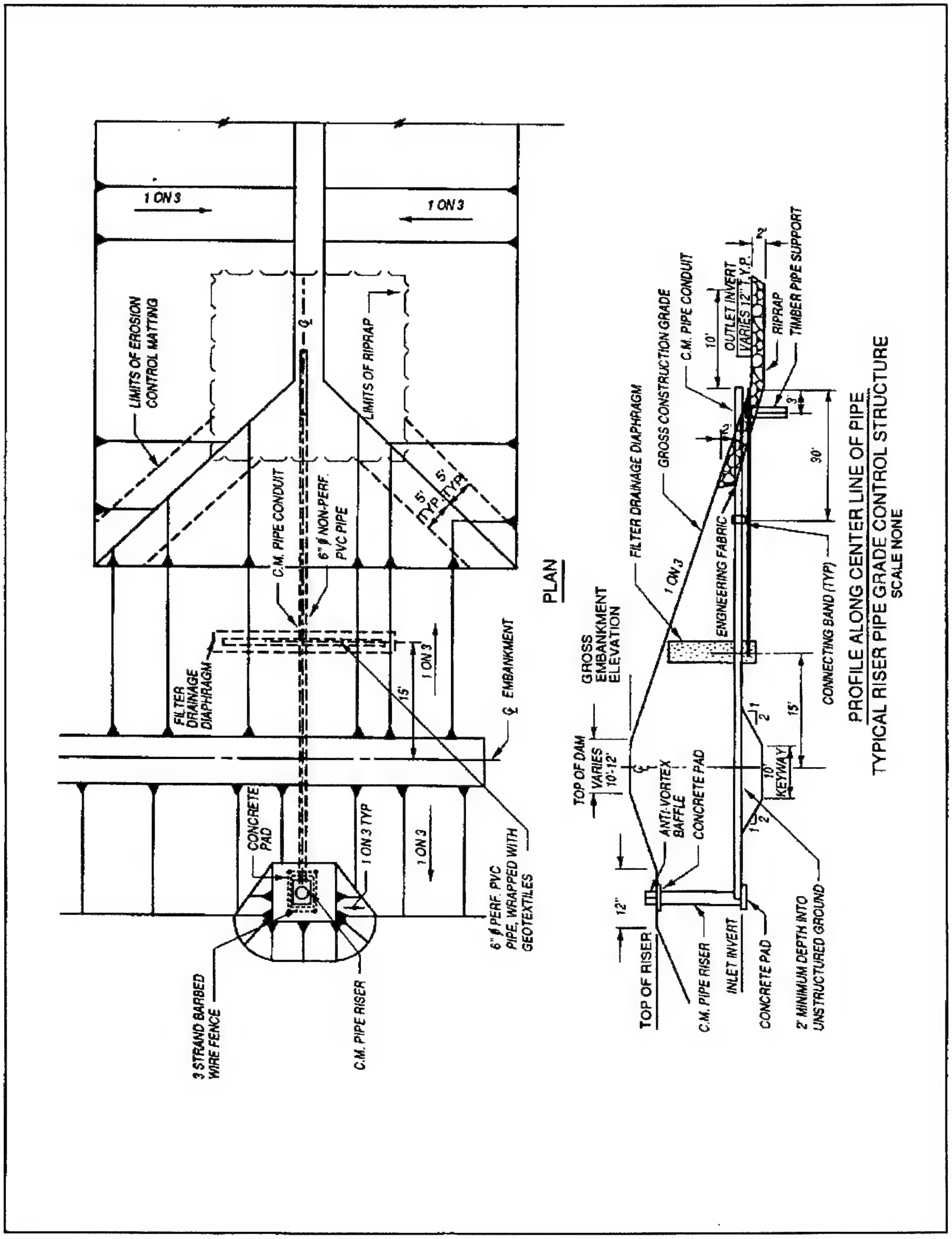


Figure 6-15. Typical riser pipe grade control structure

Figure 6-16. Concrete-lined channel on alluvial fan below debris dam (looking downstream)

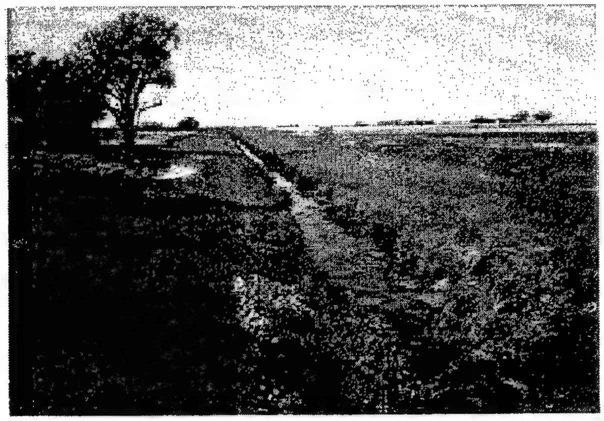


Figure 6-18. Compound cross section with low-flow channel, grassed berms, and leaves

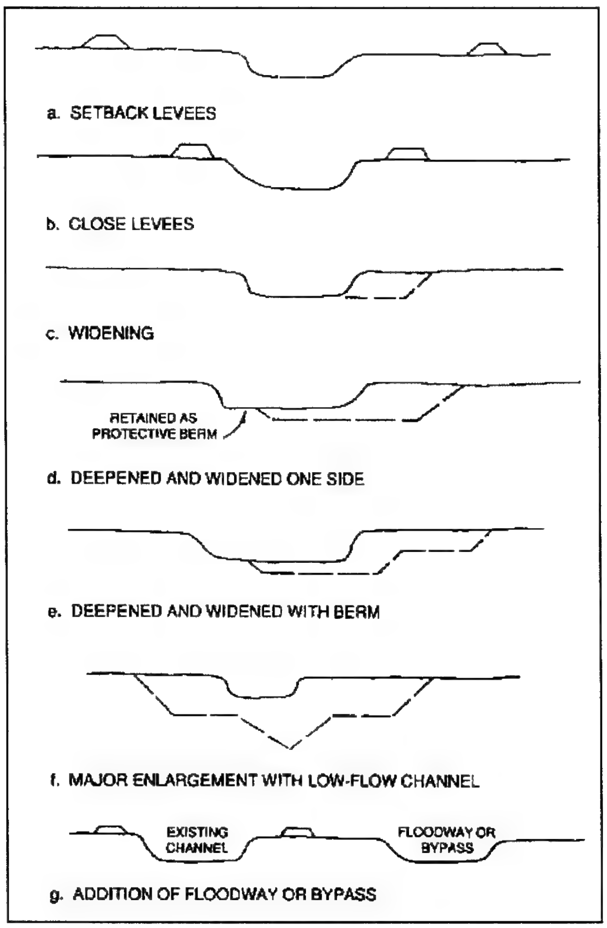


Figure 6-17. Various types of modified cross sections

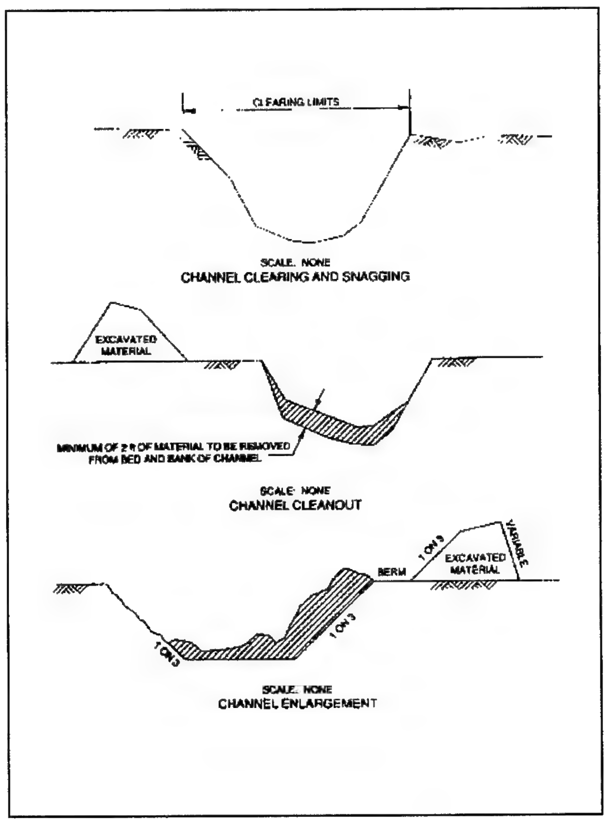


Figure 6-19. Increasing channel capacity in environmentally sensitive areas

(Figure 6-20) where only selected vegetation is removed. Selective clearing will in many cases allow desirable vegetation to remain with only minor losses in channel capacity over total clearing. An example is leaving selected larger trees on a spacing that does not seriously hamper the flow capacity of the channel. The channel bottom is cleared of all woody vegetation while the bank is selectively cleared.

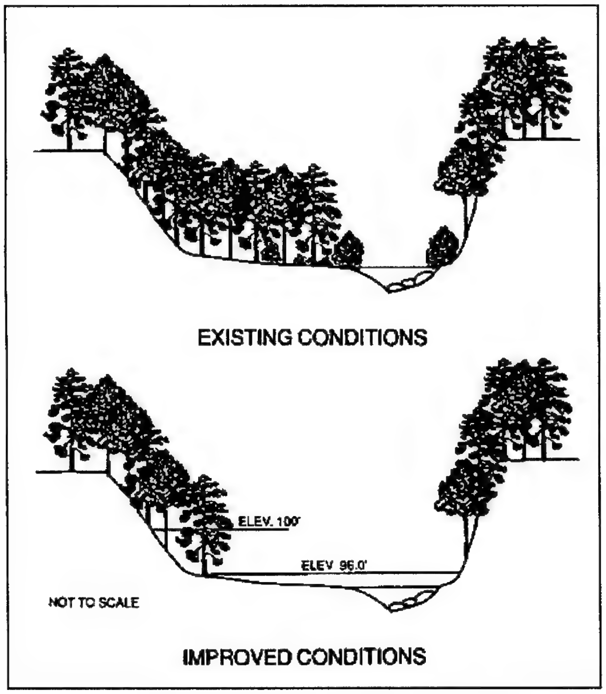


Figure 6-20. Selective clearing and snagging

(3) Channel cleanout. Channel cleanout (Figure 6-19) is similar to clearing and snagging in that all vegetation is removed from the channel bottom and at least one bank. However, the improvement is carried farther in that material is excavated from the channel also. Typically a given thickness of material, 2-3 ft in most cases, is excavated from the channel bottom. The excavation depth is tapered to near zero at top bank of the channel. In many cases all work is performed from one bank only, which allows the opposite bank to remain undisturbed. The top width of the channel remains essentially unchanged. Figure 6-19 shows a typical cross section of a channel cleanout compared to clearing and snagging and conventional channel enlargement.

(4) Projects such as the Upper Steele Bayou Basin in the U.S. Army Engineer District, Vicksburg, have been designed using this concept. The project area contains a particularly sensitive area through which additional flows must pass for the project to operate. Conventional channel enlargement downstream of the sensitive area resulted in sufficient lowering of flood flow lines to permit the use of a selective clearing and snagging alternative within the sensitive reach. Selective clearing and snagging of the environmentally sensitive reach was sufficient to offset the increase in peak flow resulting from conventional channel enlargement upstream of the area. This allowed areas adjacent to the sensitive area to achieve some flood stage reductions and provided a sufficient outlet for the conventional channel enlargement in the upstream areas.

(5) While not providing the degree of flood stage reduction attainable through conventional channel enlargement, selective clearing and snagging of environmentally sensitive reaches may provide a means by which an otherwise unacceptable project can be constructed. This concept has met the approval of both environmental and flood control proponents as an acceptable compromise between protecting the environment and providing flood control.

6-9. Control of Meandering

a. Development and migration of meanders is a major stability problem in many flood control projects. This often results from continuation or aggravation of a pre-existing situation. Tolerable pre-existing meander migration may become troublesome in a project context because it threatens flood control levees. Pre-existing meandering may be aggravated because increased channel-forming discharge tends to increase the meander wavelength and amplitude and rate of migration, or because natural bank protection has been disturbed by project works or accompanying land-use changes. For example, clearing and snagging or channel enlargement often reduces the erosion resistance of stream banks and leads to accelerated meandering. Redevelopment of meanders is a common problem in streams that have been straightened or realigned (Figures 3-6 and 6-21). If a channel is made too wide, the low-water channel may develop submeanders (Figure 3-21) that can gradually progress to full meanders by erosive attack on the banks.

b. There is an apparent paradox about certain aspects of meandering. It might seem logical that high slopes and velocities would cause more rapid meander shifting. However, it is noticeable that streams with flat slopes and relatively low velocities often have very active meanders, and that meandering tends to be more extreme in backwater zones, for example, upstream of confluences and reservoirs.

Figure 6-21. Redevelopment of meanders in straightened channel following side bar development

c. Several points about dealing with meandering in project design and maintenance are discussed in (11-(5)) below.

(1) The best solution is to locate levees outside the meander belt. This is not always possible, however. In some cases the meander belt may occupy the entire valley bottom. In other cases the meander belt may widen after construction due to factors mentioned in *a* above. Sometimes the pattern of future meander shifting is difficult to predict.

(2) Levees can be set back as far as possible from the existing channel, and a minimum distance between the levees and eroding riverbanks can be specified, with an understanding that protection works will be initiated when this minimum is reached at any point. In the case of the Tanana River at Fairbanks, Alaska, a deferred construction agreement provides for construction of groins when the specified minimum setback is encroached upon.

(3) Short lengths of bank revetment at points of active river attack are not usually effective in the long term. The attack usually shifts to other points and tends to outflank the short revetments. As these are extended, the end result is protection of the entire project length.

(4) An intermittent form of bank protection, such as groins, is usually more economical than continuous revetment. Although groins tend to cause flow disturbances that are sometimes unacceptable for navigational reasons, they appear to be beneficial to fisheries because they provide diversity of flow depths and shelter zones of low velocity during high flows.

(5) Bank vegetation and root systems provide effective protection against rapid meander shifting in many natural streams. Vegetation should not be disturbed unless there is no reasonable alternative. In the case of channel enlargement, excavation on the inner bank only (see Figure 3-3) enables retention of protective vegetation on outer banks. Where existing vegetation has to be removed, it may be feasible to replant. However, biological restorative techniques that are successful in small streams are not always transferable to larger channels. EM 1110-2-1205 should be consulted for guidance.

6-10. Bank Protection

a. Artificial bank protection is used to control meandering, to protect channel banks and levees against velocities and shear stresses that are too high for the bank materials, or to prevent toe scour and removal of berms that would encourage progressive bank failure due to geotechnical factors such as gravity slumping and seepage (Figure 6-22).

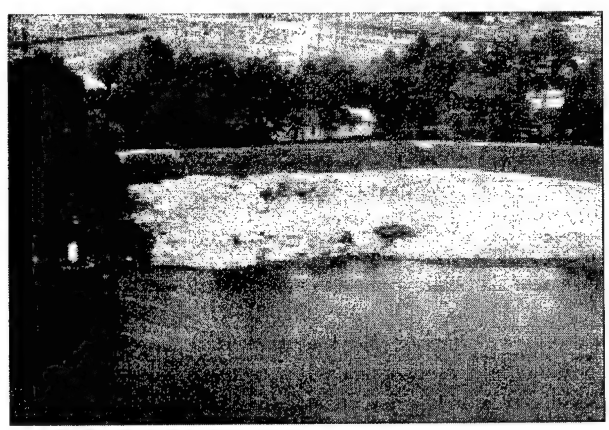


Figure 6-22. Revetment necessitated by encroachment of bank caving on levee

b. Only general comments on bank protection are made herein. More extensive information is given in Petersen (1986), and riprap bank protection is covered in EM 1110-2-1601. EM 1110-2-1205 discusses various

methods from an environmental viewpoint. Ports (1989) discusses various aspects of bank erosion and protection.

c. Methods of bank protection can be divided into continuous types such as revetment and discontinuous types such as groins (Figure 6-23). Materials include rock riprap, natural or planted vegetation, concrete, and fabricated or patented systems.

Figure 6-23. Combined use of continuous toe protection and intermittent groins

d. Failure of riprap bank protection is often due to underscouring at the toe. Galay, Yaremko, and Quazi (1987) give a detailed discussion of riprap protection in relation to toe scour. EM 1110-2-1601 provides guidance on weighed toe construction details.

e. In meandering streams, bank protection is usually provided initially only on the outer banks. The protection should be extended far enough upstream and downstream to avoid outflanking (Figure 6-24).

6-11. Control of Sediment Deposition

a. Loss of designed flood conveyance by sediment deposition is a common problem. It often occurs as a result of longitudinal instability (see paragraphs 6-3 through 6-6), or as a result of enlargements that reduce the capacity of the channel to transport sediment arriving from upstream through the project length. Flood

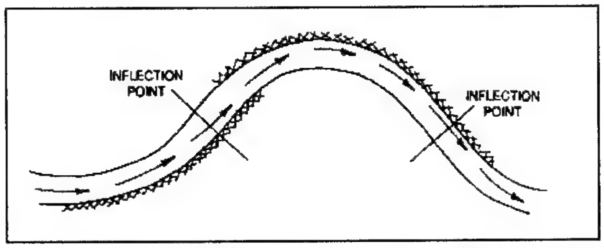


Figure 6-24. Extension of outer bank protection downstream of inflection points

diversions, high-level bypasses, or offstream detention reservoirs may also reduce the sediment transport capacity of the main channel. Deposition may occur in unmodified channel reaches downstream from the project because of increased sediment delivery from bank erosion or bed degradation within the project length.

b. Most commonly, deposition is a problem of sandy materials deposited from bed load or suspended load or both. Deposition of fine sand and silt from suspended load may be a problem on berms and in slackwater areas, as well as in estuarial and deltaic channels. Loss of conveyance due to deposition of gravel is less common generally, but is a special problem with alluvial fans in hilly terrain (see paragraph 6-6). Alteration of the nature and location of sediment deposits due to upstream works may adversely affect fish habitat in gravel-bed rivers (Milhous 1982).

c. Methods of controlling sedimentation include the following:

(1) Design of flood control channels that are capable of properly conveying the postproject sediment loads that will be imposed on the system.

(2) Debris basin at the upstream end of project, designed to capture part of the bed material load. It must be evacuated periodically. See EM 1110-2-1601 for details.

(3) Sediment retention structures, grade control structures, etc., in the headwaters and tributaries.

(4) Soil conservation measures in the watershed, including legislation to control sediment production from land use and developments.

(5) Periodic excavation or dredging of the project channel. It is necessary to ensure that a single flood

cannot deposit enough material to compromise the flood protection. The cleanout zone can be localized by excavating a sediment trap at one or more points. This approach may be necessary when the problem involves sedimentation downstream of the project.

d. In the case of levee projects, certain types of vegetation cover on the overbank (berm) areas between the channel and the levees may encourage deposition of fine sediments from suspended load. It may be necessary to keep these areas free of dense vegetation. On the other hand, overbank vegetation may sometimes reduce sediment deposition problems in the main channel.

Appendix A
References

A-1. Required Publications

Note: References used in this EM are available on interlibrary loan from the Research Library, ATTN: CEWES-IM-MI-R, U.S. Army Engineer Waterways Experiment Station, 3909 Halls Ferry Road, Vicksburg, MS 39180-6199.

EM 1110-2-1205
Environmental Engineering and Flood Control Channels

EM 1110-2-1601
Hydraulic Design of Flood Control Channels

EM 1110-2-2400
Structural Design of Spillways and Outlet Works

EM 1110-2-4000
Sedimentation Investigations of Rivers and Reservoirs

Conversationally Oriented Real-Time Programming System (CORPS) computer programs available from U.S. Army Engineer Waterways Experiment Station, ATTN: CEWES-IM-DS, 3909 Halls Ferry Road, Vicksburg, MS 39180-6199, for several U.S. Army corps of Engineers computer systems.

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Appendix B
Basis of Certain Charts in Paragraphs 5-4 and 5-5

B-1. Example of Allowable Velocity-Depth Data for Granular Materials

The chart in Figure 5-5 has been developed using a variety of sources in an attempt to consolidate allowable mean velocities for no erosion of granular materials over a wide range of grain sizes. An earlier version appeared in Roads and Transportation Association of Canada (1973) for use in checking the adequacy of bridge waterways to avoid general scour. Figure 5-5 should be taken as indicative of trends only and not as definitive guidance for flood control channels. Channels with significant bed sediment inflows will be found to tolerate higher velocities without bed erosion. On the other hand, bank erosion may occur at considerably lower velocities than shown, particularly at channel bends. The development of the chart can be explained briefly as follows:

a. Coarse sizes (generally larger than 10 mm).

(1) The Shields number criterion for coarse sizes applies, strictly speaking, to a static flat bed condition. A Shields number value of 0.045 is adopted, corresponding to effective beginning of sediment transport but not to absolute stability. The bed roughness, expressed in terms of the grain roughness k, is assumed to be three times the median grain size D, which implies a particular type of grain size distribution.

(2) The algebraic development of the Shields number is as follows:

$$\frac{dS}{(s-1)D} = 0.045 \tag{B-1}$$

where

d = depth

S = slope

s = dry specific gravity

D = median grain size

(3) The Manning formula for mean velocity V, assuming a wide channel, is converted to replace n with k in the form (Ackers 1958)

$$\frac{V}{\sqrt{gdS}} = 8.45 \left(\frac{d}{k}\right)^{1/6} \tag{B-2}$$

where g is the gravitational acceleration.

(4) Equations B-1 and B-2 are combined to eliminate S. Then, assuming $k = 3D$ and $s = 2.6$, mean velocity is derived in terms of grain size and depth as

$$V = 10.7\ D^{1/3}\ d^{1/6} \tag{B-3}$$

where V is in feet per second and D and d are in feet.

b. Fine sizes (generally smaller than 2 mm).

(1) Allowable mean velocities for the finer sizes are difficult to develop in the same way as for the coarser sizes because the flat bed assumptions underlying the Shields relationship are not even roughly applicable to field channels.

(2) A comparison of published velocity-depth data for the finer sizes shows considerable discrepancies between experimental beginning-of-movement data (e.g., Sundborg 1956), empirical ("regime") data based on field experience of stable sand-bed canals (e.g., Blench 1957), and semitheoretical data for stable channels (e.g., White, Paris, and Bettess 1981b).

(3) The curves for the fine size range in Figure 5-5 generally indicate higher allowable velocities than experimental beginning-of-movement data, but lower velocities than regime canal data. They are reasonably comparable with the semitheoretical predictions of White, Paris, and Bettess (1981b) for live-bed channels with a relatively low bed sediment concentration, in the order of 40 parts per million by weight.

B-2. Tentative Guide to Width-Discharge Relationships for Erodible Channels

a. The chart in Figure 5-9 is based on a general relationship first formulated by Lacey (1929-30) whereby, comparing one channel with another, bank-full width or wetted perimeter varies as the square root of a discharge

parameter, that is $W = C\,Q^{0.5}$, where W is the width, Q is the discharge, and C is a coefficient. The discharge parameter is variously given in the literature as dominant discharge, channel-forming discharge, or bank-full discharge. Numerous subsequent investigations of channels in different environments have confirmed the approximate applicability of the Lacey relationship, although a generally accepted theoretical explanation is lacking. Figure B-1 shows a consolidated data plot by Kellerhals and Church (1989) that covers an extremely wide range of discharges, of which the middle part closely follows the Lacey relationship.

b. The factors that affect the coefficient C in the Lacey relationship are not well defined. In general, channels with easily erodible banks, and with higher transport of bed material, tend to be wider. The curves in Figure 5-9 make allowance for bank erodibility but not for sediment transport. Coefficients are varied from 2.7 to 1.6 according to the nature of the channel banks. Curve 3 (C = 2.7) corresponds approximately to Lacey's original equation for channels in sandy alluvium. Curve 2 (C = 2.1) corresponds closely to an equation by Simons and Albertson (1963) for channels with cohesive bed and banks. Curve 1 (C = 1.6) is close to a relationship by Kellerhals (1967) for lake-outlet channels with gravel-paved or cobbled bed and banks.

c. In a set of similar curves presented by Hey and Thorne (1986) for gravel-bed channels in the United Kingdom (Figure B-2), variation in the Lacey coefficient C is associated with type of bank vegetation rather than with type of bank material. Vegetation is defined generally in terms of the percentage of tree-shrub cover, and their fitted C values, converted to ft-sec units, range from 2.34 to 4.33. It is evident that this basis for discrimination would not be generally applicable in arid climates. (Another basis that has been suggested is the percentage of silt/clay in bank materials.)

B-3. Tentative Guide to Depth-Discharge Relationships for Alluvial Channels

a. The chart in Figure 5-10 is based loosely on a comparable chart presented in a previous report (Northwest Hydraulic Consultants 1982), assuming wide channels with mean depth equivalent to hydraulic radius. Figure 5-10 should be taken as indicative of trends only for channels with low bed sediment transport, and not as definitive guidance for the design of flood control channels.

b. The source chart (Figure B-3) was based on selected relationships in the literature for a range of channel materials. Figure B-3 can be summarized as follows. Curves 1 and 2 are based on Lacey's (1929-30) original equations, with "silt factors" for medium and very fine sand respectively. Curves 3, 4, and 5 are based on Simons and Albertson's equations as quoted by USDA (1977) for (3) sand bed and banks, (4) sand bed and cohesive banks, and (5) cohesive bed and banks. Curves 6 and 7 are based on Kellerhals' (1967) equation for stable gravel-paved channels, using D_{90} values of 0.1 ft and 1 ft, respectively. (Curve 8 is irrelevant to the present discussion.)

B-4. Tentative Guide to Slope-Discharge Relationships for Erodible Channels

a. Figure 5-11 should be taken as indicative only for channels with low bed-sediment transport, and not as definitive guidance for the design of flood control channels.

b. The curves for gravel and cobble materials with median grain sizes from 20 to 200mm are based on combining the Shields criterion for beginning of movement with a Lacey-type width relationship and the Manning formula. The algebraic development, assuming a trapezoidal cross section, is as follows:

(1) Shields Number

$$\frac{dS}{(s-1)\,D} = 0.045 \qquad \text{(B-1 bis)}$$

For $s = 2.6$, Equation B-1 transforms to

$$S = 0.072\,\frac{D}{d} \qquad \text{(B-4)}$$

(2) Lacey width relation

$$b = 1.8\,Q^{1/2} \qquad \text{(B-5)}$$

where b is the mean width in feet and Q is in cubic feet per second.

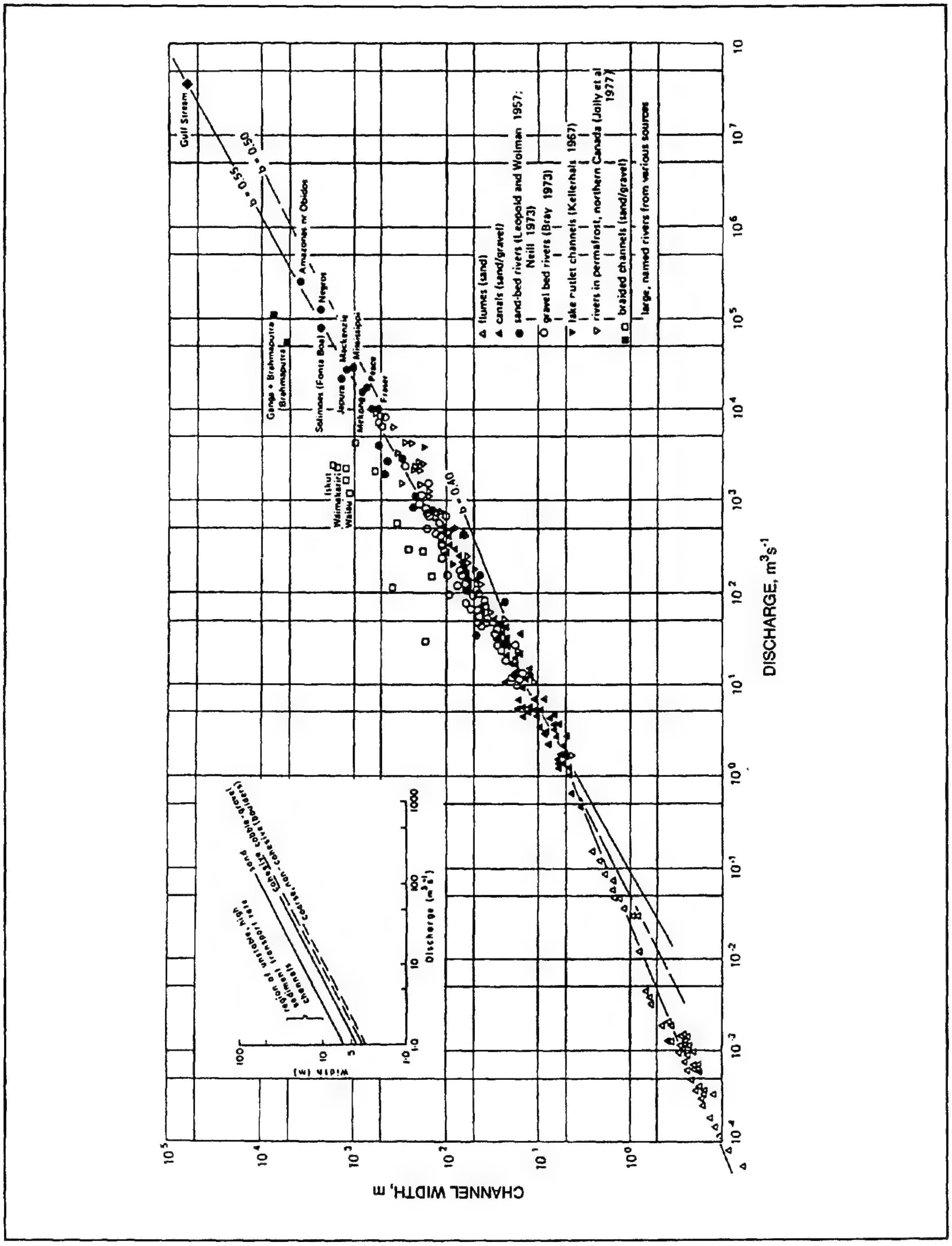

Figure B-1. Consolidated width discharge plot by Kellerhals and Church (1989)

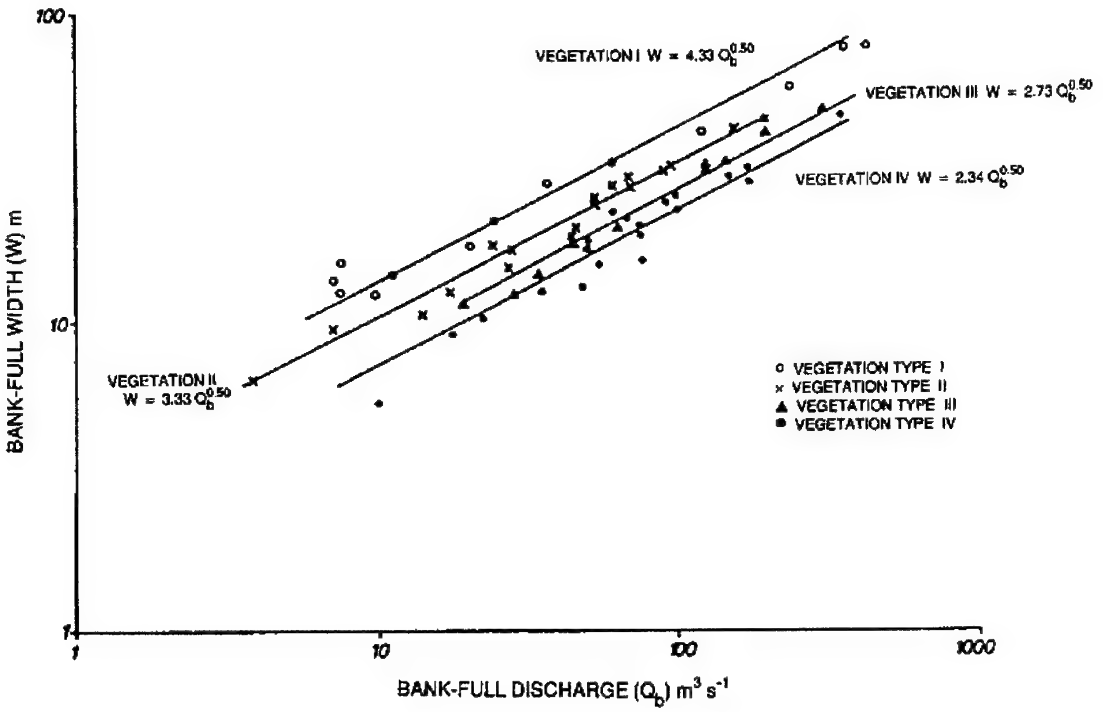

Figure B-2. Width-discharge plot by Hey and Thorne (1986), using bank vegetation as basis of discrimination; courtesy of American Society of Civil Engineers

(3) Manning formula

$$V = \frac{1.486}{n} R^{2/3} S^{1/2} \tag{B-6}$$

where n is Manning's roughness and R is hydraulic radius. Assume roughness $k = 3D$, and $n = k^{1/6}/32$ where k is in feet, then Equation B-6 transforms to

$$V = 40 \frac{R^{2/3} S^{1/2}}{D^{1/6}} \tag{B-7}$$

With the further assumption that $R = 0.9d$, Equations B-4, B-5, and B-7 may be combined with the equation of continuity, $Q = bdV$, to yield beginning-of-movement slope in terms of grain size and discharge:

$$S = 0.854 \frac{D^{1.286}}{Q^{0.429}} \tag{B-8}$$

c. The curve for medium sand is based on Lacey's formula for sandy alluvial canals

$$S = \frac{0.000547}{Q^{1/6}} \tag{B-9}$$

but multiplied by 1.3 to accord better with data for flat-slope sand-bed rivers. The curve for fine sand is drawn to give slopes about 60 percent of those for medium sand. The curves for coarse sand and for 10-mm material are interpolated arbitrarily.

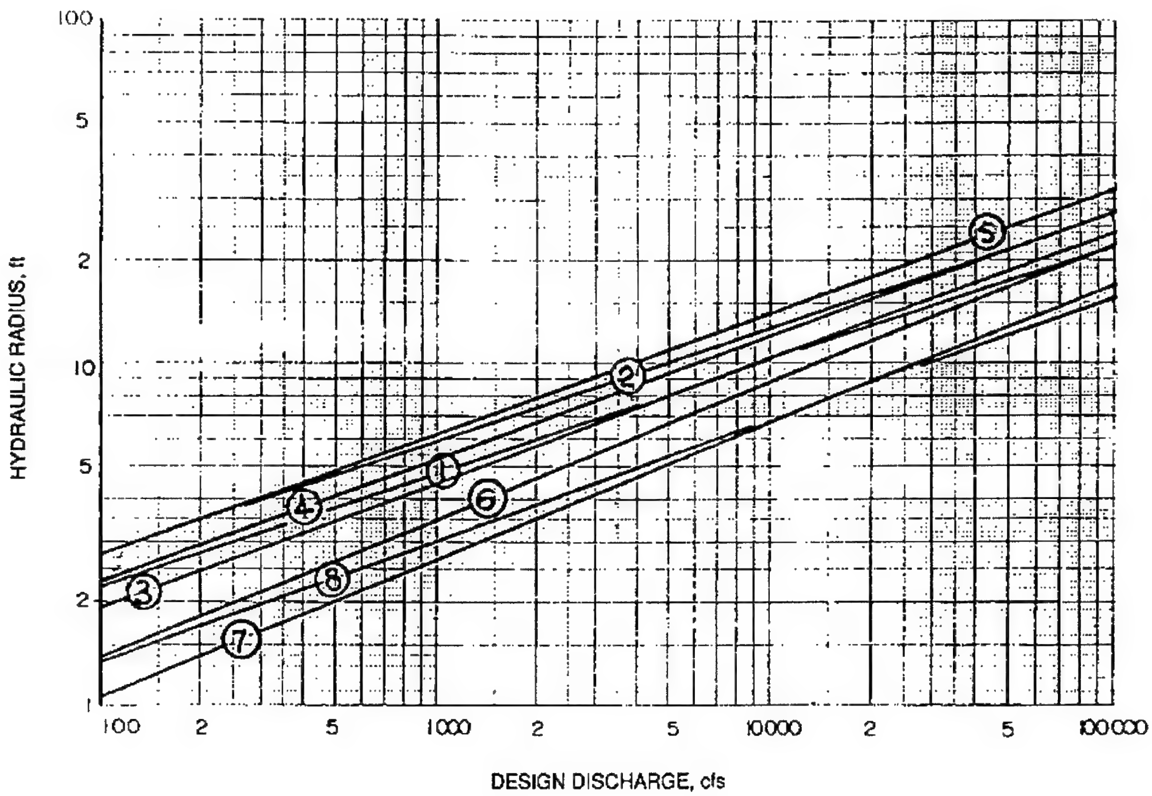

Figure B-3. Chart used as partial basis for Figure 5-10 (from Northwest Hydraulic Consultants 1982)

Appendix C Examples of Quantitative Stability Evaluation

C-1. Introduction

a. This fictional example illustrates a preliminary stability evaluation, using methods and approaches outlined in Chapter 5, for an existing channel, Varmint Creek, that is to be modified for flood control. To simplify the presentation, the analysis is given only for a reach at the downstream end of the project. In an actual case, the channel would be divided into reaches according to significant changes in hydrology, sediment inflows, slope, cross section, or roughness.

b. It is advisable to use several methods to analyze channel stability and then compare results. However, not all methods are applicable to every channel. In this example, analyses are conducted to assess which stability criteria may or may not be applicable. The next step is to use those methods that are judged applicable to assist in checking or determining the properties of a modified channel and the need for erosion control measures.

c. The format of the example follows loosely the systematic procedures outlined in paragraphs 5-10 through 5-12. In practice, descriptions would be supplemented with maps and photographs.

C-2. Description of Area and Existing Channel System

a. Drainage basin. The project area is 320 square miles at the downstream end. Slopes are generally flat. Soils are sandy soils with no rock outcrops. Land use upstream of the project is primarily row crops and pasture. The floodplain adjacent to the channel is wooded throughout the project length. One major tributary enters Varmint Creek near the upstream end of the project. There are no existing reservoirs, flood control works, or bank protection. Varmint Creek enters a lake 5 miles downstream of the project. The basin lies on the margin of a major metropolitan area and the land will be developed into low-density subdivisions. Very significant changes in land use are therefore expected during the life of the project.

b. Project reach. The existing single channel has an irregular sinuous planform but no clearly recognizable meander bends. The invert slope is 2.5 ft/mile or 0.00047. A representative bank-full cross section has a bottom width of 50 ft, surface width of 170 ft, and depth of 12 ft. The low-flow channel averages 20 ft wide by 2 ft deep. There are frequent sandy point bars with growth of grass and low brush, but no extensive deposits of fresh sand on the channel bottom. Bed and bank material is largely sand, with enough silt and clay to support dense brush on banks and point bars. Large trees on floodplain extend back 100 to 200 ft from top of banks, except for occasional recent clearings.

c. Hydrology. The mean annual rainfall is 45 in. Mean monthly temperatures range from 50 to 80 degrees Fahrenheit. The stream gauge near the downstream end of the project has 45 years of record. The largest known flood peak was 26,000 cfs in 1929. The largest recent flood was 10,000 cfs in 1984. Flood hydrology is expected to change considerably as a result of predicted basin land use change from crop and pasture to urban residential. Table C-1 shows both existing and predicted flood frequency estimates.

Table C-1
Flood Frequencies for Varmint Creek

	Peak Discharge, cfs	
Flood Frequency, Years	Existing Conditions	Future Conditions
2	4,500	15,000
10	12,500	24,000
50	26,000	42,000

d. Sediment. The stream gauge has a 10-year record of suspended sediment with a mean annual yield 48,000 tons or 150 tons per square mile, mostly a wash load of silt and clay. There are no data on bed load. Bed material is medium to coarse sand, D_{50} = 0.5 mm. Bank material consists mainly of fine to medium sand with about 10 percent silt/clay.

e. Hydraulic roughness. The overall Manning's n for the existing channel is estimated to be 0.04 at bank-full stage, based partly on calibration against high-water marks using HEC-2. For overbank flow on the floodplain, the estimate is 0.08. The high channel roughness is due partly to dunes and ripples in the sand bed, partly to brush vegetation between the low-water channel and the floodplain, and partly to channel irregularities involving flow expansions and eddy formation.

C-3. Existing Instabilities

No serious sheet erosion or significant point sources of sediment were observed during a basin reconnaissance. There is very little bank instability in the project length of channel where natural tree and brush vegetation remains on the floodplain. Where vegetation has recently been cleared locally by landowners, some slumping and erosion have occurred.

C-4. Key Features of Proposed Project

a. The initial basic proposal is to widen and deepen the existing channel while maintaining the existing alignment and slope. The initially proposed trapezoidal cross section has a 200-ft bottom width, 1V:3H side slopes, and a 16-ft depth. It is designed to carry the future conditions 10-year flood within the channel, assuming a Manning *n* value of 0.03.

b. This initial proposal has been developed to meet hydrologic and hydraulic criteria, without special regard to stability evaluation. Based on general principles of channel response (Chapter 2) and experience elsewhere (Chapter 3), it might be expected to cause considerable problems with stability unless erosion control measures are incorporated (Chapter 6). The much larger in-channel discharge and the reduced channel roughness under future conditions will lead to considerably greater velocities; and the existing vegetation, which provides a certain degree of erosion protection, will be removed by channel enlargement.

C-5. Screening of Methods for Analysis of Existing Channel

In the following paragraphs, several technical approaches described in paragraph 5-3 are applied in skeleton form to the existing channel under bank-full conditions. In practice, computations would be more extensive.

a. Allowable velocity-depth approach.

(1) Compute bank-full mean velocity by Manning formula

$$A = 12(50 + 170)/2 = 1{,}320 \text{ square feet (ft}^2\text{)} \qquad \text{(C-1)}$$

$$P = 50 + 2\sqrt{12^2 + 60^2} = 172.4 \text{ ft} \qquad \text{(C-2)}$$

$$R = A/P = 1320/172.4 = 7.66 \text{ ft} \qquad \text{(C-3)}$$

$$\begin{aligned} V &= 1.486 \times 7.66^{.667} \times 0.00047^{.5}/0.04 \\ &= 3.1 \text{ ft/second (sec)} \end{aligned} \qquad \text{(C-4)}$$

where

A = cross-section area

P = wetted parameter

R = hydraulic radius

V = mean velocity

(2) According to Figure 5-5, the allowable mean velocity for no significant erosion, using a grain size of 0.5 mm and a depth of 12 ft, is approximately 2.9 ft/sec. Comparison with the computed cross-sectional mean velocity of 3.1 ft/sec suggests that even under bank-full conditions the potential for bed erosion is relatively small. This result does not appear to conflict seriously with field observations. However, local mean-on-vertical velocities will be considerably higher in the center of the channel, where local roughness is likely to be substantially less than the assumed overall value, and near the outer bank in bends.

b. Allowable shear stress (tractive force) approach.

(1) Compute average boundary shear stress:

$$\begin{aligned} \gamma R S &= 62.4 \times 7.66 \times 0.00047 \\ &= 0.22 \text{ pounds (lb)/ft}^2 \end{aligned} \qquad \text{(C-5)}$$

where

γ = specific weight of water

s = slope

(2) The boundary Reynolds number based on grain size (Figure 5-3) works out to approximately 20, for which the curve in Figure 5-3 indicates a Shields number (dimensionless shear stress) of 0.033 for beginning of bed movement. The allowable shear stress is then computed as

$$\begin{aligned} &0.033 \times 62.4 \times 1.6 \times 0.5/304.8 \\ &= 0.0056 \text{ lb/ft}^2 \end{aligned} \qquad \text{(C-6)}$$

(3) According to this crude application, therefore, the channel bed should be highly erodible because the actual shear stress at bankfull is about 60 times greater than allowable for no erosion. However, crude application of the Shields diagram is very misleading for this type of natural channel, because the diagram implies a flat bed with total roughness determined by the sand grains, which would result in a Manning's n value on the order of 0.015. The estimated actual Manning's n is much larger because it is largely determined by bed forms, channel irregularities, and vegetation.

(4) A more realistic assessment using the allowable shear stress approach can be arrived at using empirical data based on field observations. In the absence of data based on local experience, use could be made of a diagram for canals in granular materials that has been reproduced widely in the literature (Figure C-1). Using the upper curve for canals with high fine sediment content, the allowable shear stress is approximately 0.09 lb/ft^2, which is much closer to the computed average channel value of 0.22 lb/ft^2. The ratio of actual to allowable shear stress is still substantial, suggesting active bed transport under bank-full conditions.

(5) More extensive computations for a range of conditions can be facilitated using the personal computer program SAM as referred to in Chapter 5. Table C-2 shows example results, in terms of hydraulic parameters for the existing channel and overbank at a number of discharges ranging from existing bankfull to future conditions 50-year flood.

c. Empirical relationships for channel properties.

(1) Bank-full discharge Q can be estimated as

$$\begin{aligned} Q &= V \times A = 3.1 \times 1{,}320 \\ &= 4{,}092 \text{ cubic feet per second (cfs)} \end{aligned} \tag{C-7}$$

This is close to the estimated 2-year flood peak of 4,500 cfs. The 2-year flood will therefore be adopted as the channel-forming discharge for purposes of checking against Figures 5-9 through 5-11. On this basis, the existing bank-full surface width, mean depth, and slope are shown plotted on those charts in Figure C-2.

(2) The width point is near Curve 3 for sandy alluvial banks, which appears compatible with the actual situation. The mean depth is close to the curve for coarse sand. The slope is somewhat high but not unexpectedly so, given that there is probably significant bed material transport under bank-full flows.

(3) These comparisons indicate that the properties (hydraulic geometry) of the existing bank-full channel are sufficiently close to general empirical relationships that these may be used in an initial assessment of the proposed project channel.

d. Analytical relationships for channel properties.

(1) A manual check against analytical relationships for alluvial channel properties can be made using the tables of White, Paris, and Bettess (1981b). Using the table for 0.5 mm sand (Table C-3) and entering with a discharge of 130 centimeters per second (cms) (4,500 cfs) and a slope of 0.00047 (0.47 per 1,000), the associated bed sediment concentration can be determined by graphical interpolations to be approximately 180 parts per million (ppm) by weight - not a large concentration for a sand-bed stream. The predicted bank-full surface width is roughly 50 meters (m) (164 ft) which is nearly right. The predicted bankfull depth is roughly 2.5 m (8 ft), which is too low. (As previously noted, the actual depth is high because of additional roughness caused by vegetation.)

(2) Analytical predictions can also be checked using an option in the computer program SAM, as described in paragraph 5-6. The channel-forming discharge and the bed sediment grain size are input with trial values of bed sediment concentration; required secondary input parameters for this procedure are the average side slope and roughness of the banks, adopted here as 1V:5H and 0.045, respectively. For each trial value of sediment concentration, a table of alternative, hydraulically feasible channel properties is obtained, as in Table C-4. The sediment concentration C is varied until a plot of tabulated slope versus width passes through the data point representing the actual channel (Figure C-3). In this case a reasonable match was obtained with a sediment concentration of 150 ppm, which checks reasonably against the result in (1) above using the White tables. Table C-4, obtained using this concentration, approximates the actual channel properties on the fourth line.

(3) The SAM method does not give a unique solution of channel width, depth, and slope unless the hypothesis of minimum stream power is accepted. Results using this hypothesis are shown in the last line of Table C-4. In this case, minimum stream power appears to require a much wider, shallower, and flatter channel than actually exists. It can be argued that minimum stream power hypothesis is not applicable because of high roughness due to in-channel vegetation and because the banks are partly protected by vegetation.

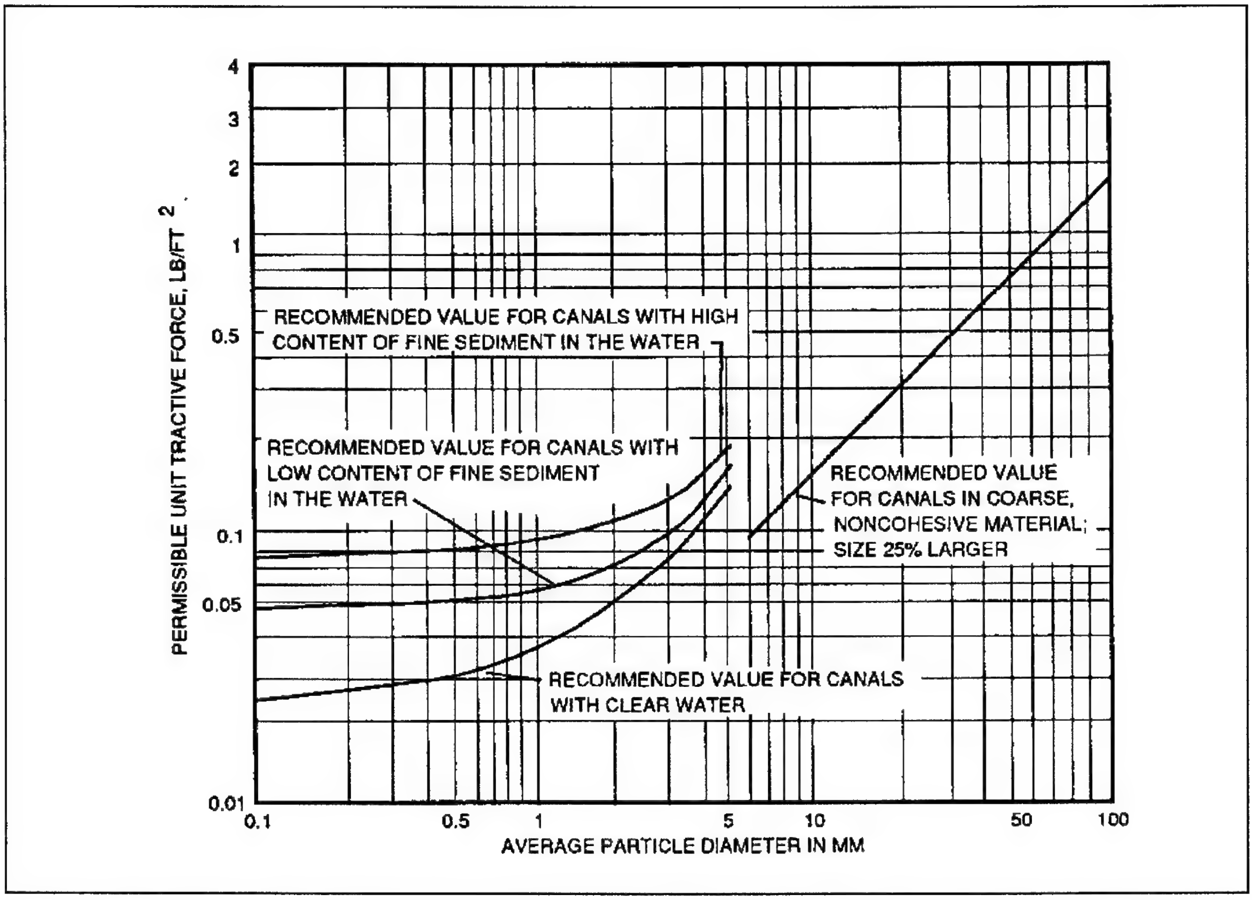

Figure C-1. Allowable shear stresses (tractive forces) for canals in granular materials (Chow 1959), courtesy of McGraw-Hill)

e. Conclusions regarding appropriate methods.

(1) The allowable velocity and allowable shear stress methods appear to be of limited applicability, because the channel probably has an appreciable bed sediment concentration under bankfull conditions, as well as a rather nonuniform transverse distribution of roughness and velocity due to the presence of in-channel vegetation.

(2) Empirical relationships for the properties of channels with small bed material loads appear to fit the existing channel well with respect to width. Depth is greater than predicted, probably because of high roughness. Slope is also greater than predicted, probably because of bed sediment inflows and transport.

(3) Analytical methods exemplified by the White tables and the SAM computer program allow better matching of channel properties by using bed sediment concentration as a variable. Reasonable matching is obtained with a concentration of around 150 ppm by weight.

C-6. Preliminary Evaluation of Proposed Project Channel

a. The initially proposed bank-full surface width (see C-4 above) is 200 + 6 × 16 = 296 ft, and the computed mean depth is 13.4 ft. These are plotted on the width and depth charts of Figure C-2 assuming the future-conditions 2-year flood of 15,000 cfs as channel forming. The placement in relation to the curves is similar to that of the existing channel, suggesting that the proposed width and depth are acceptable on a preliminary basis. For similar placement on the slope chart, however, the slope of the proposed channel would have to be reduced to around 0.00035.

Table C-2
Computed Hydraulic Parameters Using SAM Program

				Top Composite		Slope Composite				
		Q cfs	Water Surface Elevation ft	Width ft	R ft	ft/ft	n value	Velocity fps	Froude Number	Sheer Stress lb/ft^2
Channel OB	Strip No.			Effective Width	Effective Depth	Slope	n value	Effective Velocity		
Channel	1	4500.	12.14	1661.4	10.70	.000470	.0561	2.79	.15	.31
OB	1	4479		121	10.66	.000470	.0410	3.45		
	2	21		1490	.14	.000470	.0799	.11		
Channel	2	12500.	15.58	1695.8	9.24	.000470	.0841	1.69	.08	.27
OB	1	7424		145	13.11	.000470	.0425	3.90		
	2	5076		1500	3.58	.000470	.0759	.95		
Channel	3	15000.	16.31	1703.1	9.34	.000470	.0820	1.74	.08	.27
OB	1	8116		149	13.64	.000470	.0428	3.99		
	2	6884		1502	4.30	.000470	.0796	1.07		
Channel	4	24000.	18.42	1724.2	10.18	.000470	.0775	1.96	.09	.30
OB	1			160	15.21	.000470	.0429	4.30		
	2			1508	6.40	.000470	.0789	1.40		
Channel	5	26000.	18.84	1728.4	10.42	.000470	.0769	2.00	.09	.31
OB	1	10961		162	15.52	.000470	.0429	4.35		
	2	15039		1510	6.81	.000470	.0789	1.46		
Channel	6	42000.	21.71	1740.0	12.45	.000470	.0741	2.34	.10	.36
OB	1	14859		1758	17.83	.000470	.0436	4.76		
	2	27141		1518	9.67	.000470	.0789	1.85		

b. Use of the White data (Table C-3) for a discharge of 425 cms (15,000 cfs) and a sediment concentration of 150 ppm suggests a surface width of about 90 m (295 ft), a depth of about 3.8 m (12.5 ft), and a slope of about 0.00035. The width and slope check well with the analysis in *a* above.

c. The SAM computer program, using the same bed sediment grain size (0.5 mm) and concentration (150 ppm) as for the existing channel, produces the lower curve shown in Figure C-3. For minimum stream power (corresponding to minimum slope), the channel properties are *bottom* width 280 ft, depth 13 ft, and slope 0.00020. As in the case of the existing channel (see C-5 above), the minimum stream power hypothesis requires a wider, shallower, and flatter channel.

d. Hydraulic calculations using the Manning formula indicate that the mean channel velocity at 2-year flood conditions is increased from about 3.2 ft/sec in the existing channel to about 5.1 ft/sec in the proposed channel.

e. These preliminary indications from several methods of analysis suggest that the proposed channel is likely to encounter stability problems and that consideration needs to be given to two design features: bank protection to prevent widening and the development of meandering, and grade controls to reduce the effective hydraulic slope.

f. Consideration also needs to be given to erosion potential under 10-year and higher flow conditions. The proposed channel has a bank-full capacity of 24,000 cfs, the future-conditions 10-year flood (see C-4 above). For this flow the mean velocity is over 6 ft/sec, about twice that in the existing bank-full channel.

g. The question arises as to whether it is appropriate to assume the same bed sediment concentration for the future-conditions channel as for the existing channel. Depending on various factors that are difficult to predict, future sediment concentrations might be greater or smaller than existing.

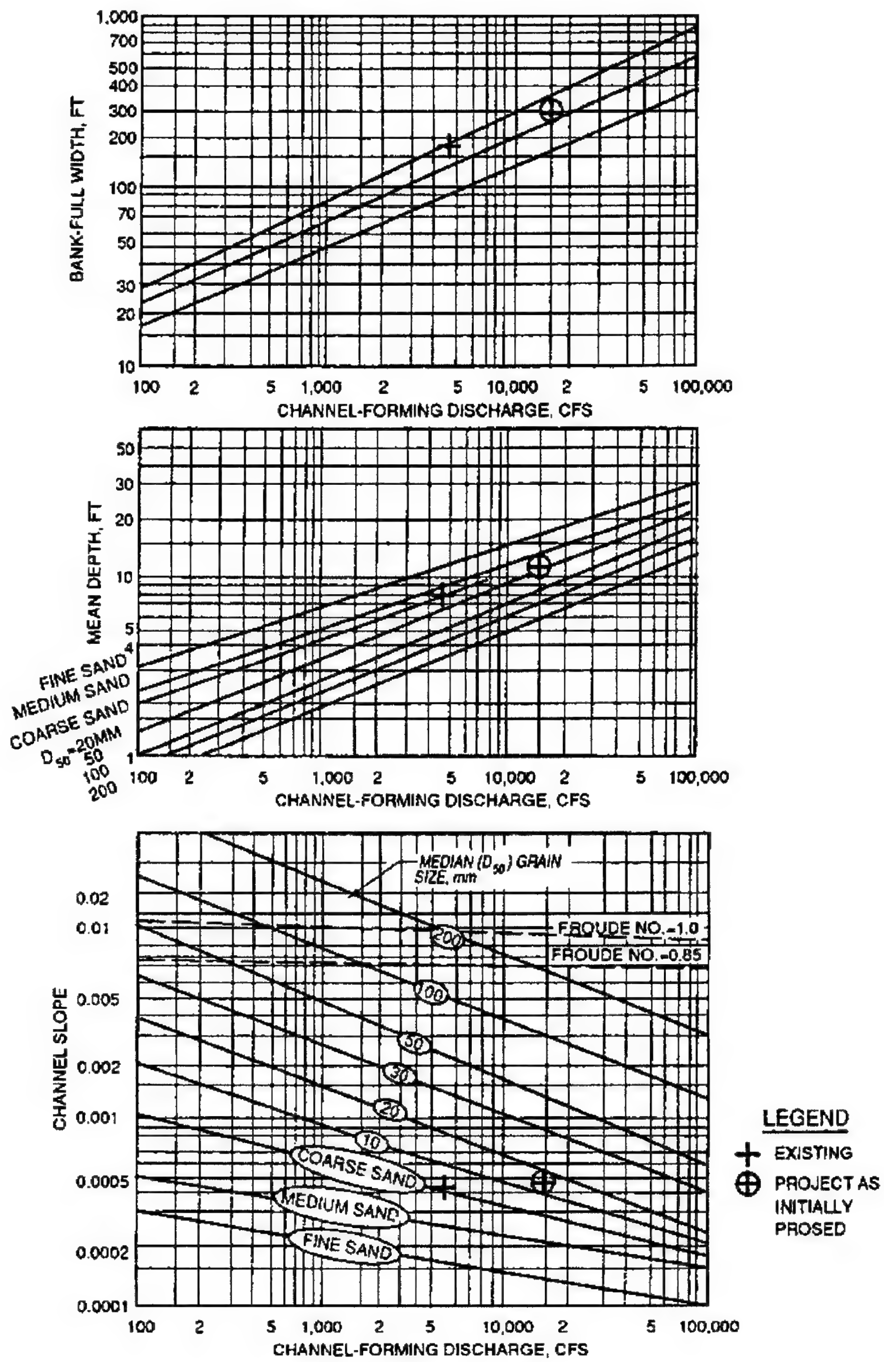

Figure C-2. Varmint Creek channel properties compared with tentative width, depth, and slope charts from paragraph 5-5

Table C-3
Table of Predicted Channel Properties for 0.5 mm Bed Material From White, Paris, and Bettess (1981b)

SAND SIZE 0.50 MILLIMETRES

AREA OF TABLE ENCOMPASSING VARMINT CREEK EXISTING CHANNEL

SEDIMENT CONCENTRATION (PPM)	DISCHARGE (CUMECS) 0.5	1.0	2.0	5.0	10.0	20.0	50.0	100.0	200.0	500.0	1000.0
10	0.45 0.237 0.46 2.4 0.323	0.47 0.191 0.62 3.4 0.321	0.50 0.156 0.81 5.0 0.322	0.53 0.121 1.15 8.2 0.320	0.56 0.101 1.51 11.8 0.324	0.60 0.086 1.96 17.1 0.329	0.64 0.070 2.76 28.2 0.338	0.68 0.060 3.57 41.0 0.346	0.73 0.053 4.59 59.8 0.354	0.81 0.045 6.60 93.8 0.370	0.86 0.040 8.24 141.9 0.376
20	0.47 0.309 0.42 2.5 0.372	0.49 0.256 0.56 3.6 0.372	0.52 0.214 0.73 5.3 0.375	0.56 0.171 1.05 8.5 0.381	0.60 0.146 1.36 12.4 0.387	0.63 0.126 1.76 17.9 0.395	0.69 0.106 2.47 29.3 0.405	0.74 0.094 3.20 42.2 0.415	0.79 0.083 4.12 61.1 0.424	0.88 0.073 5.74 99.2 0.436	0.95 0.066 7.35 143.3 0.445
40	0.49 0.425 0.38 2.7 0.441	0.52 0.360 0.51 3.8 0.445	0.55 0.307 0.66 5.5 0.449	0.60 0.253 0.93 9.0 0.457	0.64 0.222 1.21 13.0 0.465	0.68 0.196 1.57 18.6 0.473	0.75 0.168 2.20 30.2 0.485	0.81 0.151 2.84 43.3 0.494	0.88 0.137 3.64 62.3 0.502	0.98 0.122 5.06 100.4 0.513	1.09 0.113 6.67 137.7 0.522
60	0.50 0.524 0.36 2.8 0.490	0.53 0.449 0.47 4.0 0.494	0.57 0.389 0.61 5.7 0.500	0.62 0.326 0.87 9.2 0.509	0.67 0.289 1.13 13.2 0.517	0.72 0.258 1.46 19.1 0.526	0.80 0.225 2.03 30.8 0.536	0.87 0.204 2.63 43.8 0.545	0.94 0.187 3.38 62.6 0.553	1.06 0.168 4.70 100.3 0.561	1.16 0.156 6.07 143.0 0.567
80	0.51 0.615 0.34 2.9 0.529	0.55 0.532 0.45 4.0 0.534	0.59 0.464 0.59 5.8 0.540	0.66 0.395 0.87 8.8 0.554	0.69 0.351 1.07 13.5 0.557	0.75 0.316 1.38 19.3 0.565	0.84 0.278 1.93 31.0 0.576	0.91 0.254 2.48 44.3 0.583	0.99 0.254 3.20 62.8 0.589	1.12 0.211 4.46 99.9 0.597	1.24 0.197 5.71 141.8 0.600
100	0.52 0.699 0.33 2.9 0.562	0.57 0.611 0.45 3.9 0.571	0.60 0.536 0.56 5.9 0.573	0.66 0.458 0.79 9.5 0.582	0.72 0.412 1.02 13.8 0.589	0.78 0.371 1.32 19.5 0.597	0.87 0.328 1.85 31.1 0.607	0.95 0.302 2.38 44.3 0.613	1.04 0.279 3.05 63.1 0.618	1.18 0.253 4.26 99.7 0.624	1.30 0.237 5.47 140.9 0.627
200	0.56 1.078 0.29 3.0 0.677	0.61 0.958 0.38 4.3 0.682	0.66 0.858 0.49 6.2 0.687	0.73 0.751 0.69 9.9 0.694	0.80 0.684 0.89 14.0 0.700	0.87 0.628 1.15 19.9 0.704	0.99 0.566 1.61 31.6 0.709	1.08 0.526 2.06 44.8 0.711	1.20 0.491 2.67 62.5 0.712	1.37 0.452 3.72 98.1 0.711	1.52 0.426 4.76 137.9 0.709
400	0.62 1.734 0.26 3.2 0.813	0.66 1.572 0.32 4.8 0.829	0.73 1.427 0.43 6.3 0.817	0.83 1.274 0.61 10.0 0.820	0.91 1.176 0.78 14.2 0.820	1.00 1.092 1.00 20.0 0.820	1.14 0.998 1.39 31.6 0.817	1.27 0.938 1.81 43.4 0.813	1.41 0.882 2.32 61.5 0.808	1.62 0.819 3.23 95.3 0.798	1.81 0.778 4.14 133.2 0.789
600	0.64 2.336 0.23 3.4 0.919	0.72 2.127 0.31 4.5 0.902	0.79 1.951 0.40 6.4 0.900	0.89 1.757 0.56 10.1 0.897	0.98 1.633 0.71 14.2 0.894	1.09 1.527 0.93 19.7 0.889	1.25 1.403 1.29 31.1 0.881	1.39 1.325 1.66 43.3 0.873	1.55 1.252 2.13 60.4 0.863	1.80 1.169 2.95 94.1 0.848	2.03 1.113 3.82 129.1 0.836
800	0.70 2.897 0.23 3.1 0.970	0.74 2.660 0.29 4.7 0.986	0.83 2.449 0.37 6.5 0.970	0.94 2.220 0.52 10.2 0.954	1.05 2.074 0.68 14.0 0.947	1.16 1.943 0.87 19.8 0.939	1.35 1.797 1.23 30.0 0.926	1.50 1.697 1.57 42.6 0.915	1.68 1.609 2.01 59.2 0.902	1.95 1.507 2.81 91.2 0.883	2.19 1.438 3.61 126.4 0.867
1000	0.71 3.438 0.21 3.3 1.021	0.79 3.166 0.28 4.5 1.016	0.85 2.937 0.35 6.7 1.030	1.00 2.670 0.50 9.9 0.998	1.10 2.498 0.64 14.1 0.989	1.20 2.349 0.79 21.1 0.987	1.42 2.176 1.16 30.5 0.962	1.58 2.061 1.49 42.3 0.948	1.79 1.960 1.94 57.7 0.932	2.08 1.838 2.69 89.5 0.910	2.34 1.756 3.45 123.9 0.891
2000	0.81 5.973 0.18 3.4 1.196	0.90 5.557 0.24 4.7 1.181	1.00 5.197 0.31 6.5 1.164	1.16 4.788 0.43 10.1 1.140	1.29 4.516 0.56 13.9 1.129	1.46 4.275 0.72 19.1 1.099	1.70 3.993 1.01 29.3 1.070	1.84 3.807 1.22 44.4 1.061	2.16 3.631 1.67 55.4 1.022	2.53 3.425 2.33 84.6 0.989	2.88 3.286 3.03 114.4 0.962
4000	0.94 10.608 0.16 3.3 1.382	1.05 9.963 0.21 4.6 1.352	1.18 9.392 0.26 6.4 1.323	1.37 8.738 0.37 9.9 1.282	1.55 8.285 0.48 13.4 1.250	1.74 7.886 0.62 18.6 1.218	2.06 7.410 0.87 27.9 1.174	2.32 7.088 1.12 38.3 1.141	2.71 6.794 1.52 48.7 1.102	3.13 6.433 2.04 78.1 1.063	3.56 6.185 2.64 107.1 1.045

Note: The five values given for the sediment concentration for each discharge are as follows:

Velocity, metres/sec — Slope *1000 — Depth, metres
Width, metres — Friction factor *10

Table C-4
Computed Alternative Sets of Stable Channel Properties Using SAM Program

Stable Channels for Q = 4500.0 C,ppm = 150.0 D50 = .500

K	Bottom Width ft	Depth ft	Energy Slope ft/ft	Cmpos't n-value	Hyd Radius ft	Vel fps	Froude Number	Shear Stress #/sf	Bed(2) Regime
1	13.	13.7	.000972	.0436	7.33	4.01	.19	.83	TL
2	26.	13.5	.000672	.0422	7.71	3.56	.17	.57	TL
3	39.	12.9	.000548	.0409	7.84	3.36	.16	.44	TL
4	52.	12.3	.000479	.0396	7.85	3.24	.16	.37	TL
5	65.	11.6	.000434	.0384	7.78	3.16	.16	.31	LO
6	78.	10.9	.000402	.0373	7.65	3.10	.17	.27	LO
7	91.	10.3	.000380	.0362	7.49	3.06	.17	.24	LO
8	104.	9.7	.000363	.0352	7.31	3.03	.17	.22	LO
	117.	9.2	.000351	.0343	7.11	3.00	.17	.20	LO
10	130.	8.7	.000341	.0334	6.91	2.98	.18	.19	LO
11	143.	8.3	.000334	.0327	6.70	2.96	.18	.17	LO
12	156.	7.9	.000329	.0320	6.49	2.93	.18	.16	LO
13	169.	7.5	.000325	.0313	6.29	2.92	.19	.15	LO
14	182.	7.1	.000322	.0307	6.10	2.90	.19	.14	LO
15	195.	6.8	.000321	.0302	5.91	2.88	.19	.14	LO
16	208.	6.5	.000320	.0297	5.73	2.86	.20	.13	LO
17	221.	6.3	.000319	.0293	5.55	2.84	.20	.12	LO
18	234.	6.0	.000320	.0289	5.39	2.83	.20	.12	LO
19	247.	5.8	.000320	.0285	5.23	2.81	.21	.12	LO
20	260.	5.6	.000321	.0282	5.08	2.79	.21	.12	LO
				Results at Minimum Stream Power					
21	223.	6.2	.000319	.0292	5.53	2.84	.20	.12	LO

Notes: (1) Cross Section Properties: LEFT BANK RIGHT BANK
SIDE SLOPE, [H:1V] = 5.000 5.000
Ks, FT = 5.189 5.189
n-VALUE = .04500 .04500
(2) REGIMES: LO = LOWER, TL = TRANSITIONAL-LOWER, TU = TRANSITIONAL-UPPER, UP = UPPER

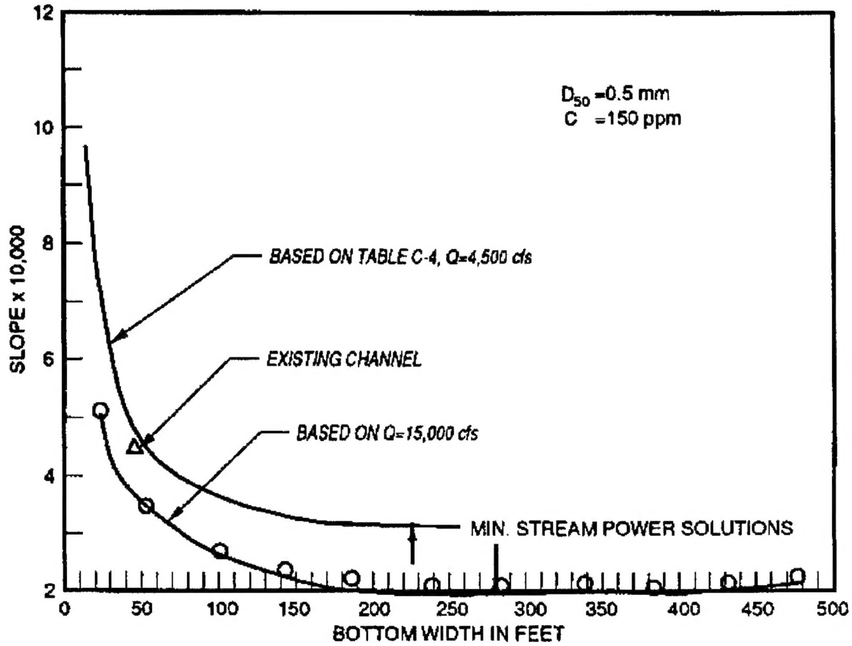

Figure C-3. Slope versus width curves for discharges of 4,500 cfs (Table C-4) and 51,000 cfs, based on output from SAM program

Appendix D
Notation

A Cross-section area

b Mean width

C Sediment concentration

d Depth of flow

D Grain size

D_{50} Median sediment size

g Gravitational acceleration

k Grain roughness

L Channel length between inflection points

n Manning's roughness

P Wetted perimeter

Q Discharge

Q_s Bed material discharge

R Hydraulic radius

s Dry relative density of sediment

S Slope; hydraulic slope

V Mean velocity

$V*$ Shear velocity defined as $\sqrt{\tau_0/\rho}$

W Width

0 Superscript indicating no change

+ Superscript indicating an increase

γ Specific weight of water

γ_s' submerged specific weight of sediment

ν Kinematic viscosity

ρ Fluid density

τ_0 Average boundary shear stress in uniform flow